Analytical Tool for the Design of Effective Amphibious Ships and Connectors

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Synopsis

The capability of projecting a military force on land, from ships located at a safe distance from the shore, without the need of using existing infrastructure such as ports, is unique and important. It is important because such operations from the sea provide great flexibility in where on land to insert the military force. However, modern weapons are an imminent danger to amphibious ships that are located near the shore. The obvious solution is to increase the ship-to-shore distance, but that also means that it will take longer to transport the landing force to the shore. Vehicles and heavy equipment have to be transported by landing craft, and making landing craft faster without affecting the condition of the people on board, especially in adverse weather, is not straightforward. What would be the best trade-off between ship-to-shore distance and time?

As illustrated by this example, the design process of amphibious ships – and the connectors that they carry – is characterised by finding an acceptable balance between the different factors that determine the operational effectiveness of the operation. The tool presented in this paper is intended to be used early in the design process. It estimates operational effectiveness by modelling the interaction between several factors: (a) the composition of the landing force: number of personnel, number of vehicles, amount of equipment, smallest unit of action; (b) the characteristics of the connectors: payload capacity, speed, number of connectors; and (c) the operational requirements: number of waves, ship-to-shore distance, and time. The tool is based on a set of analytical equations and is capable of solving these for any combination of two factors or variables. For example, the tool can estimate number of waves and time (amphibious operation planning data) or alternatively, payload capacity and speed (connector design data).

The analytical tool presented in this paper provides insight that is essential to the design of effective amphibious ships and connectors. The paper will show several applications, including comparing the wave characteristics of connectors (different types of landing craft and helicopters) and simulating a non-combatant evacuation operation (NEO) for which a mix of different types of connectors are used.

There is a need for this tool because amphibious operation requirements are often conflicting – for example ship-to-shore distance and time – which makes it difficult to find an acceptable balance between operational effectiveness, technical feasibility and affordability. Technical feasibility and affordability are not part of the analysis, but can be included in the results without great difficulty.

Keywords: operations analysis; operational effectiveness; modelling and simulation; amphibious operations; amphibious ships; connectors; landing craft

1 Introduction

1.1 Design Challenge

A critical part of an amphibious warfare operation is the transportation of a landing force (LF) from an amphibious task group (ATG) to a beach. This part of the operation is called the amphibious landing. The ATG consists of amphibious warfare ships, which are the ships that carry the LF, and other naval ships and submarines that protect the amphibious ships against various threats such as air, surface and subsurface threats and sea mines. The

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Author's Biography

Richard Logtmeijer holds the current position of Senior Staff Member Life Cycle Modelling in the Defence Materiel Organisation (DMO) of the NL Ministry of Defence. He is responsible for analysing the operational effectiveness and cost of maritime systems. He is the NL delegate to the NATO Specialist Team on Mission Modularity and the chair of the NATO Specialist Team on Naval Ship Systems Engineering. His previous experience includes three years serving as a naval officer and over twenty years working for the Royal Netherlands Navy. He has a MSc in Electrical Engineering (University of Twente, The Netherlands).

After completing a Bachelor degree in Naval architecture/engineering, in 2006 **Machiel Bussemaker** completed the Marine Corps Officer Course within the Royal Netherlands Navy. After specializing in Amphibious warfare he commanded several levels of Amphibious and infantry units within the Netherlands Marine Corps, interchanged by staff functions at Netherlands Navy Head Quarters (N7-training) and Netherlands Maritime Warfare Centre (Amphibious Warfare). In this period he was deployed to Africa, Afghanistan and the Caribbean for several types of military operation. From 2020 he holds a position at the Netherlands Defence Materiel Organisation (DMO) – Life Cycle Modelling, to support and coordinate the development of the next generation Amphibious Toolbox (Surface Assault craft and successor of the Landing Platform Dock capabilities).

Hedde van der Weg holds the current position of staff member Life Cycle Modelling in the Defence Materiel Organisation (DMO). He is working on concept development and requirements definition/elucidation in the early stage of naval ship design and procurement. He completed a MSc degree in Marine Technology from the Delft University of Technology.

amphibious ships of the ATG are the high-value units: without these units, the amphibious warfare operation cannot be successfully completed.

There are two ways to get the LF from the amphibious ships to the beach: (1) use connectors such as landing craft and helicopters to transport the LF from the amphibious ships to the beach, or (2) land the amphibious ships on the beach. Amphibious warfare ships that can land on the beach are called landing ships. Table I shows the main advantages and disadvantages of both methods.

Table I Getting the LF to the beach

Method	Advantages	Disadvantages
Use connectors	The amphibious ships can stay outside the effective range of enemy weapons. It is relatively easy to find a landing point because landing craft are small.	The amphibious landing is slow.
Land the amphibious ships	The amphibious landing is fast.	The landing ships will be within the effective range of enemy weapons. It is relatively difficult to find a landing point because landing ships are large.

The focus of this paper is on using connectors to transport the LF from the amphibious ships to the beach. The objective is to support the design of the amphibious ships and their connectors by conducting operations research and analysis.

1.2 Key Requirements

Key requirements for designing effective amphibious ships are:

- The amphibious ships are capable of carrying the LF from the home port to a location near the beach. The LF consists of personnel, vehicles, equipment, and stores.
- The amphibious ships are capable of carrying and operating connectors such as landing craft and helicopters.
- The surface connectors (landing craft) are capable of landing a sufficiently large part of the LF in a single wave in an acceptable time period. A surface wave is a single trip of the surface connectors from the amphibious ships to the beach.
- The air connectors (helicopters) are capable of landing a sufficiently large part of the LF in a single wave in an acceptable time period. An air wave is a single trip of the air connectors from the amphibious ships to the objective area on land.

The bits of text ‘sufficiently large part of the LF’ and ‘in an acceptable time period’ have to be specified with values. Usually these values follow from the requirements of the amphibious warfare operation (which includes the amphibious landing).

2 The Analytical Tool

2.1 Modelling the Amphibious Landing

The best approach to modelling is to start simple:

- There is one amphibious ship.
- The LF consists of identical atoms. An atom is composed of personnel, vehicles, equipment, and stores. For example, an atom can be composed of four troops and one vehicle. An atom is indivisible, which means that the components of the atom cannot be separated.
- The LF consists of identical units. Atoms can be grouped to form a smallest unit of action (SUA). The SUA is also indivisible. For example, if the atom is composed of four troops and one vehicle, the SUA can be two atoms, and the LF can be eight atoms.
- The amphibious ship carries connectors of one type and model (surface or air).

Figure 1 shows how an amphibious landing under these conditions can be modelled with only a few variables. The variables are listed in Table II. Note that if the connector is an air connector, the ship-to-shore distance is the distance from the amphibious ships to the objective area on land.

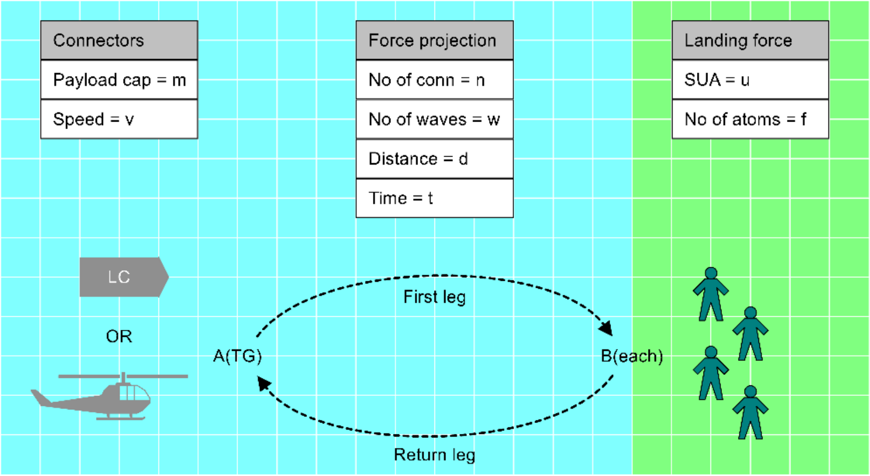


Figure 1 Modelling the amphibious landing

Table II Variables that describe a simplified amphibious landing

Variable	**Description**
u	size of landing force unit, in atoms
f	size of landing force, in atoms
m	connector payload capacity, in atoms
n	number of connectors
w	number of waves
v	average speed of connector, in kn
d	ship-to-shore distance, in nm
t	transit time, in h

Note that the variables u, f, m, n, and w hold integer values. The interactions between the variables can be described with two equations, one for transport capacity and one for transport speed:

Equation 1: transport capacity

$$\text{ceiling}\left(\frac{f}{m' \cdot n}\right) = w$$

where

$$m' = \text{floor}\left(\frac{m}{u}\right) \cdot u$$

Equation 2: transport speed

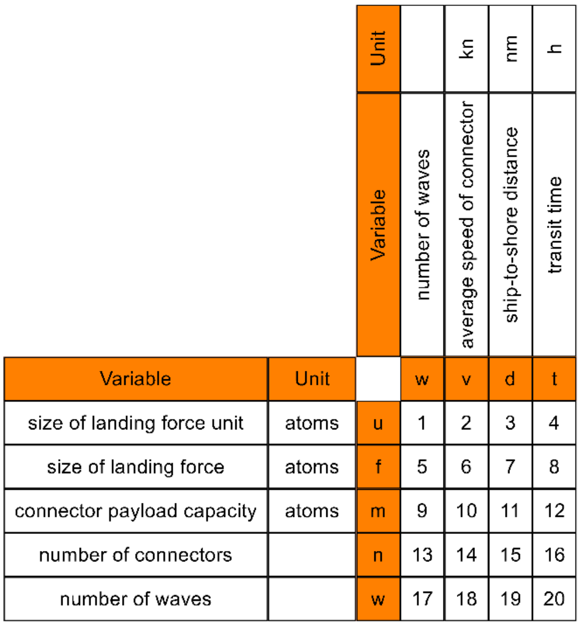
$$\text{floor}\left(\frac{v \cdot t}{2d}\right) = w$$

The function ceiling rounds a number up to the nearest integer; the function floor rounds a number down to the nearest integer.

Note that Equation 1 uses the SUA to calculate the number of atoms per connector. For example, if the connector (e.g., a helicopter) can carry ten troops and the SUA is four troops, then the number of troops per connector is eight.

The two equations can be solved for twenty different combinations of model variables. This is visualised in Figure 2. The full set of equations can be found in Appendix A. Note that the two equations share the variable w for the number of waves. There can only be one value for the number of waves; if the value of w in Equation 1 differs from the value of w in Equation 2, the set of input and output values does not represent a valid solution.

The twenty different model output options make the model versatile. For example, a user may provide a value for each of the model variables without checking the consistency and validity of the set of input values. The model can compile a list of consistent and valid solutions by calculating all twenty model output options. The user can decide which solution best fits his or her purpose. Alternatively, if the user is interested in connector design, he or she may use the model to calculate the payload capacity and average speed of the connector. Or, if the user is interested in operations planning, he or she may use the model to calculate how many connectors and waves are needed for the amphibious landing. The simplicity of the model allows the user to analyse much more than just operation completion time.



		Variable	number of waves	average speed of connector	ship-to-shore distance	transit time
		Unit		kn	nm	h
Variable	Unit		w	v	d	t
size of landing force unit	atoms	u	1	2	3	4
size of landing force	atoms	f	5	6	7	8
connector payload capacity	atoms	m	9	10	11	12
number of connectors		n	13	14	15	16
number of waves		w	17	18	19	20

Figure 2 Model output options. Example: option 10 means solving the equations for variables *m* and *v*

2.2 *Increasing Model Output Accuracy*

If the model were to be used for predicting operation completion time, the result would not be very realistic. First, because the model does not take into account embarkation and debarkation times. Secondly, because a connector does not move at the specified average speed all the time: sometimes it has to wait. For example, a landing craft may have to wait before it can enter the well dock of an amphibious ship. So for a more accurate operation completion time prediction, embarkation and debarkation times and waiting time have to be modelled. Another relevant factor to model is the relationship between connector speed and loading condition. The speed of a connector can drop significantly when it is fully loaded. For example, the speed of a landing craft can drop from 25 knots to 20 knots when fully loaded.

To accommodate these changes the simple model described previously can be extended by adding a pre-processor, a post-processor and two new variables. Figure 3 shows the structure of the extended model. The extended model also has the unique characteristic of providing different output options. The control value tells the model which output option to select, or to select all of them. The input variables of the pre-processor, the two new variables of the extended model, and the output variables of the post-processor are listed in Tables III to V, respectively. The pre-processor uses Equations 3 to 7 to convert the input values of the extended model into input values for the simple model. The post-processor uses similar equations, and a few more, to convert the output values of the simple model into output values for the extended model.

The variables *margin_f* and *margin_v* (Table V) report the margins in transport capacity and transport speed, respectively. A positive value represents a robust solution. For example, if the speed margin is positive, the calculated connector speed is below the specified average speed. This means that in case of unexpected delays, the connector can sail or fly at a higher speed.

A large difference between the last wave and the other waves of the amphibious landing (Table V) is a sign of both inefficiency and robustness. For example, if the wave transport capacity is ten troops and the landing force consists of 21 troops, the actual transport capacity of the last wave will be one troop. That is inefficient. However, if for some reason the actual wave transport capacity drops to eight troops, the loss can be compensated in the last wave – which is a sign of robustness.

The variables *t_ins* and *t_ext* (Table V) report insertion and extraction times, respectively. Insertion time is measured from the point in time when the first connector arrives at the beach till the point in time when the last connector leaves the beach (Figure 4). The time of landing of the first connector is called H-hour in case of surface connectors, and L-hour in case of air connectors. The LF is on land at H-hour + *t_ins* (surface) or L-hour + *t_ins* (air).

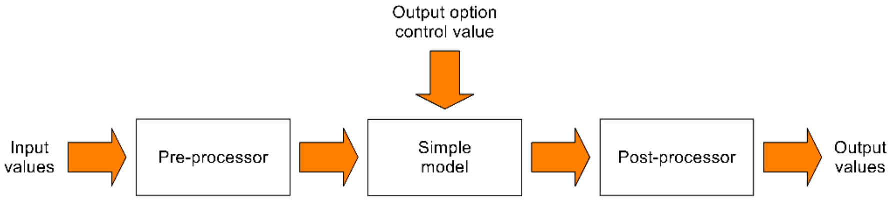


Figure 3 Extended model structure

Table III Pre-processor input variables

Variable	**Description**
u, f, m, n, w	See Table II
v_unl	connector speed unloaded, in kn
v_loa	connector speed loaded, in kn
dx	ship-to-shore distance along x-axis, in nm
dy	ship-to-shore distance along y-axis, in nm
t_alo	completion time of amphibious landing operation, in h
t_emb_atom	embarkation time of one atom, in h
t_deb_atom	debarkation time of one atom, in h
n_emb	number of connectors that can be embarked at the same time
n_deb	number of connectors that can be debarked at the same time
t_wfl	waiting time on first leg, in h
t_wrl	waiting time on return leg, in h

Table IV New variables of the extended model

Variable	**Description**
rv	ratio of speed unloaded and speed loaded
rd	ratio of distance along y-axis and distance along x-axis

Table V Post-processor output variables

Variable	**Description**
u, f, m, n, w	See Table II
v_unl, v_loa, dx, dy, t_alo	See Table III
margin_f	margin of landing force size, in atoms
margin_v	margin of connector average speed, in kn
t_flu	completion time of first leg, unloaded, in h
t_fll	completion time of first leg, loaded, in h
t_rlu	completion time of return leg, unloaded, in h
t_rll	completion time of return leg, loaded, in h
wo_n_atoms	number of atoms of wave other than last wave

wo_t_emb	embarkation time of wave other than last wave, in h
wo_t_deb	debarkation time of wave other than last wave, in h
wo_t	completion time of wave other than last wave, in h
wl_n_atoms	number of atoms of last wave
wl_t_emb	embarkation time of last wave, in h
wl_t_deb	debarkation time of last wave, in h
wl_t	completion time of last wave, in h
t_ins	completion time of landing force insertion, in h
t_ext	completion time of landing force extraction, in h

Equation 3: average speed of connector

$$v = \frac{2 \cdot v_{unl} \cdot v_{loa}}{v_{unl} + v_{loa}}$$

Equation 4: ship-to-shore distance

$$d = \sqrt{{d_x}^2 + {d_y}^2}$$

Equation 5a: embarkation time

$$t_{emb} = \frac{f}{n_{emb}} \cdot t_{emb\_atom}$$

Equation 5b: debarkation time

$$t_{deb} = \frac{f}{n_{deb}} \cdot t_{deb\_atom}$$

Equation 6: waiting time

$$t_{wait} = \left(t_{wfl} + t_{wrl}\right) \cdot w$$

Equation 7: transit time

$$t = t_{alo} - t_{emb} - t_{deb} - t_{wait}$$

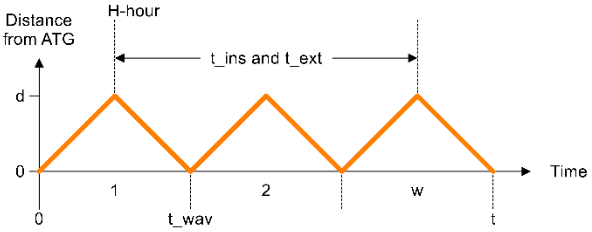


Figure 4 Insertion and extraction times

2.3 Wave Characteristics

The extended model shown in Figure 3 has twenty output options. One of these options is to calculate the size of the landing force and the transit time (variables *f* and *t*). With this option the wave characteristics of a given connector model in a given scenario can be calculated. Wave characteristics are the transport capacity and turnaround time associated with a single wave of the amphibious landing (turnaround time is the duration of a round trip starting from the amphibious ship). The wave characteristics determine whether a given connector model is capable of landing a sufficiently large part of the LF in a single wave in an acceptable time period (see Section 1.2 on Key requirements). In the design phase of amphibious ships and their connectors, the challenge is to find a cost-effective mix of connector models (surface and air). The effectiveness (and cost) of different connector models, both existing models and new designs, should be analysed. To support this activity, the input dataset of the extended model (Table III Pre-processor input variables) was split into a scenario dataset and a connector dataset (Tables VI and VII, respectively). A new model, called the Landing Wave Model or LWM, calculates the wave characteristics of every connector model listed in the scenario dataset. The scenario data and connector data are merged by connector model and atom type (to distinguish between a Landing Craft, Vehicle Personnel carrying troops and the same LCVP carrying vehicles, for example). The LWM uses the extended model shown in Figure 3, which is called the Amphibious Landing Model or ALM, for each row of the merged dataset. The output dataset contains the wave characteristics of the different connector models, and can be used to compare and contrast connector effectiveness. Effectiveness is expressed in transport capacity per unit of time (*wo_n_atoms* divided by *wo_t*, see Table V Post-processor output variables).

Table VI Scenario dataset

Variable	**Description**
model	connector model
atom	civilian (CIV), military (MIL) or vehicle (VEH)
u	size of landing force unit, in atoms
n	number of connectors
dx	ship-to-shore distance along x-axis, in nm
dy	ship-to-shore distance along y-axis, in nm
n_emb	number of connectors that can be embarked at the same time
n_deb	number of connectors that can be debarked at the same time
t_wfl	waiting time on first leg, in h
t_wrl	waiting time on return leg, in h

Table VII Connector dataset

Variable	**Description**
type	connector type
name	connector name
model	connector model
atom	civilian (CIV), military (MIL) or vehicle (VEH)
m	connector payload capacity, in atoms
v_unl	connector speed unloaded, in kn
v_loa	connector speed loaded, in kn
t_emb_atom	embarkation time of one atom, in h
t_deb_atom	debarkation time of one atom, in h

2.4 Mixed Landing Cycles

The ALM was developed for the transportation of a homogeneous LF from one origin to one destination, using connectors of one type and model. For example, the model can simulate the transportation of identical vehicles from an amphibious ship to a landing zone, using two Landing Craft, Utility of model X. However, a real amphibious landing can be more complex:

- The LF is transported from several amphibious ships (origins).
- The LF is transported to several destinations (on the beach and/or on land).
- An amphibious ship carries connectors of different types and models (surface and/or air). For example, an LSD carries LCU, LCVP, boats and helicopters (LSD: Landing Ship, Dock; LCU: Landing Craft, Utility; LCVP: Landing Craft, Vehicle Personnel).
- The LF is heterogeneous.

To simulate the more complex situation, the amphibious landing can be decomposed into LF components that meet the model requirements: one atom type, one origin, one destination, and connectors of one type and model. This may result in having to distribute the LF over different origins that are actually at the same location. Figure 5 illustrates the potential problem: how many troops have to be assigned to each of the helicopter and boat lanes? To avoid this question, a new model, called the Mixed Landing Cycles model or MLC, was developed. The MLC can simulate the transportation of a homogeneous LF from one origin to different destinations, using connectors of different types and models (Figure 5). The landing cycles along the different surface and air lanes will be different, hence the name of the model. The MLC does not have the versatility of the ALM: it can only be used to simulate when certain events of the amphibious landing occur (discrete-event simulation).

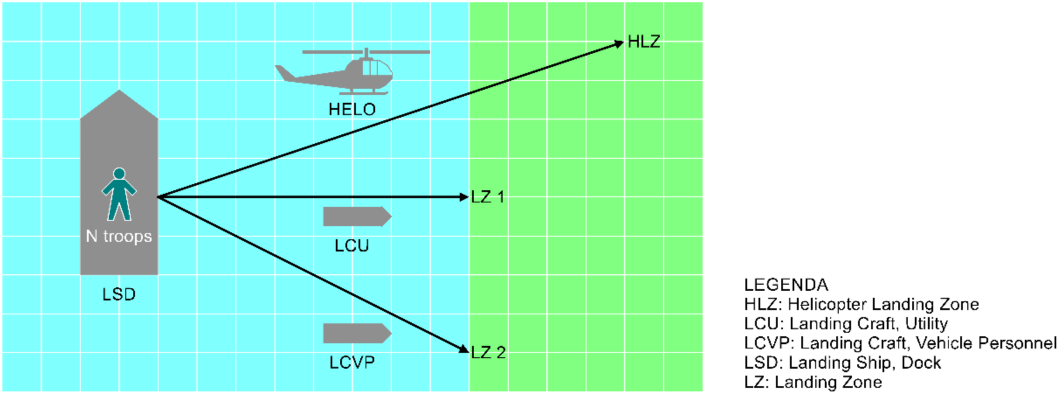


Figure 5 Mixed landing cycles

Table VIII shows the required input. The MLC uses the wave characteristics of the connectors that are involved in the amphibious landing (Table IX). The wave characteristics are generated by the LWM. Each connector moves through a series of landing cycle stages:

- Insertion: stop or go > embarkation > transit loaded > debarkation > transit unloaded, or stop or go > stop
- Extraction: stop or go > transit unloaded > embarkation > transit loaded > debarkation, or stop or go > stop

If a connector completes the last stage, it returns to the stop or go stage and the model determines how many atoms of the LF component are available for transportation. If that number is zero, the next stage is stop.

To make different connectors in the first wave arrive at their destinations at the same time (H-hour and/or L-hour), the start times of the connectors can be delayed (Table VIII).

The MLC uses the wave characteristics data to determine how much time is spent at each landing cycle stage. The output of the MLC is a record of events (Table X). The number of events can be large; therefore the model can also summarise the record of events. The summary shows for each connector (a) the time passed before reaching the stop stage; (b) the number of waves completed, and (c) the number of atoms of the LF component inserted or extracted (Table XI).

Table VIII Mixed Landing Cycles model input

Variable	**Description**
wav_char	wave characteristics of connector models
n_atoms	number of atoms to insert or extract
ins	insertion (TRUE) or extraction (FALSE) operation
t_start	start times of connector models, in h

Table IX Wave characteristics dataset

Variable	**Description**
model	connector model
t_flu	completion time of first leg, unloaded, in h
t_fll	completion time of first leg, loaded, in h
t_rlu	completion time of return leg, unloaded, in h
t_rll	completion time of return leg, loaded, in h
wo_n_atoms	number of atoms of wave other than last wave
wo_t_emb	embarkation time of wave other than last wave, in h
wo_t_deb	debarkation time of wave other than last wave, in h

Table X Record of events

Variable	Description
t	time, in h
model	connector model
start_of	landing cycle stage that starts at t
wave	wave number
n_origin	number of atoms at origin
n_assigned	number of atoms assigned to connectors
n_embarked	number of embarked atoms
n_dest	number of atoms at destination

Table XI Summary of the record of events

Variable	Description
model	connector model
t	time, in h
n_waves	number of waves
n_atoms	number of atoms inserted or extracted

2.5 Non-combatant Evacuation Operation

A Non-combatant Evacuation Operation or NEO is a military operation aimed at evacuating non-combatants from an area where their lives are in danger. The NEO is conducted when the normal routes away from the area are no longer available. For example, when all commercial flights from the local airport are cancelled, and roads are blocked. In the case of a NEO from the sea, which is a special case of an amphibious landing, the non-combatants are asked to go to an agreed location near the shore, at an agreed time. Marines and/or special forces are landed in the first wave of the NEO; their task is to meet with the non-combatants, protect them and help them with embarking the connectors. A NEO from the sea can be simulated with the MLC. Note that in the case of an extraction operation such as a NEO, the origin is the landing zone on the beach or on land (Figure 5).

Typical characteristics of a NEO are: (a) the number of non-combatants can be in the thousands; (b) the operation is conducted under severe time pressure; and (c) the operation is a stop-and-go operation: it is frequently interrupted by periods of waiting time. The stop-and-go characteristic can be included by inserting periods of waiting time into the simulation results. The time pressure characteristic can be modelled with a casualty rate, which is the number of non-combatants who become casualties per unit of time. This approach is useful for planning the NEO because the total number of non-combatants rescued is a good measure of effectiveness for comparing alternative NEO designs.

To implement the casualty rate, two new input variables have been added to the MLC (Table XII). The total number of casualties is determined by (a) the casualty rate, (b) the time that passes before the evacuation operation can start, and (c) the extraction time (see Figure 4 Insertion and extraction times). The number of non-combatants who become casualties in a time interval of length t is given by Equation 8. Note that the equation uses the round-off error from the previous time interval in order to accurately calculate the number of casualties. It is assumed that non-combatants who are assigned to a connector and waiting for embarkation, are excluded from the equation because they are protected by the marines and/or special forces.

The MLC was used in a NATO study about the relationship between (a) force element and task group design and (b) operational effectiveness (Duchateau and Logtmeijer, 2022). The casualty rate feature of the MLC was used for evaluating the NEO effectiveness of the task group. In the study the availability of amphibious ships and connectors to the evacuation operation depended on the amount of damage sustained from passing through a minefield, which in turn depended on the design of the force elements.

Table XII Input variables for modelling a NEO under severe time pressure

Variable	Description
casu_rate	casualty rate, in atoms / h
t_passed	time passed before start of operation, in h

Equation 8: no of casualties

$$no\_of\_casualties = \min(y, no\_of\_non\_combatants)$$

where

$$y = \mathrm{floor}(x)$$
$$x = casualty\_rate \cdot t + error$$
$$error = x - y$$

3 Implementation and Application Examples

The three models were built as code for R. R is a language and environment for statistical computing and graphics (The R Foundation, 2022). The main reason for choosing R is that R includes important tools to do data science, for example tools for visualising and exploring model output data. The models can be shared under the terms and conditions of a government-to-government agreement.

The following examples demonstrate the functionality of the three models. All data in the examples are fictitious and any resemblance to reality is purely coincidental.

3.1 Example 1: Defence Planning

The first example is about defence planning. Defence Planning is ensuring that a nation and its operations planners will have the required capabilities available to meet its objectives in an uncertain future (Sartzis, 2019). Suppose there is a need for “a new type of aircraft, that could not only take off and land vertically but also could carry combat troops, and do so at speed.” (Kass, 2022). Table XIII shows the notional requirement for the tactical movement of troops by this Next Generation Rotorcraft (a rotorcraft is a rotary-wing aircraft such as a helicopter). Using output option 10 of the ALM, it can be found that the Next Generation Rotorcraft must be capable of carrying 32 fully equipped troops at a cruise speed of 176 kn.

Table XIII Requirement for the Next Generation Rotorcraft

Variable	**Value**
u	4 troops
f	64 troops
m	capacity seated: ? troops
n	2 rotorcraft
w	1 wave
v_unl, v_loa	cruise speed: ? kn
dx	100 nm
dy	0 nm
t_alo	2:00
t_emb_atom, t_deb_atom	30 s
n_emb, n_deb	2 rotorcraft
t_wfl, t_wrl	10 min*

*The waiting time does not include refuelling (which may take up to 20 minutes). Therefore the combat range of the rotorcraft must be at least the distance to the objective area times the number of waves (in this case 100 nm).

3.2 Example 2: Comparing and Contrasting Connector Effectiveness

Before starting the design of the Next Generation Rotorcraft and determining feasibility, it is a good idea to check whether there exists a military off-the-shelf product that meets the requirement. In this example twelve rotorcraft are compared and contrasted; one of them is the Next Generation Rotorcraft. The specifications of the military off-the-shelf rotorcraft can be found in Appendix B. Figure 6 shows the wave characteristics of the rotorcraft, each operated in the scenario as specified in Table XIII. The wave characteristics are calculated by the LWM. Note that the wave characteristics depend on the scenario. To illustrate this, Figure 6 also shows the results for a 25 nm and 50 nm distance to the objective area. Figure 7 shows the effectiveness of the rotorcraft, expressed in number of troops transported per hour, for the requirement of 100 nm distance to the objective area. There is in this example only one rotorcraft that is more effective (Figure 8).

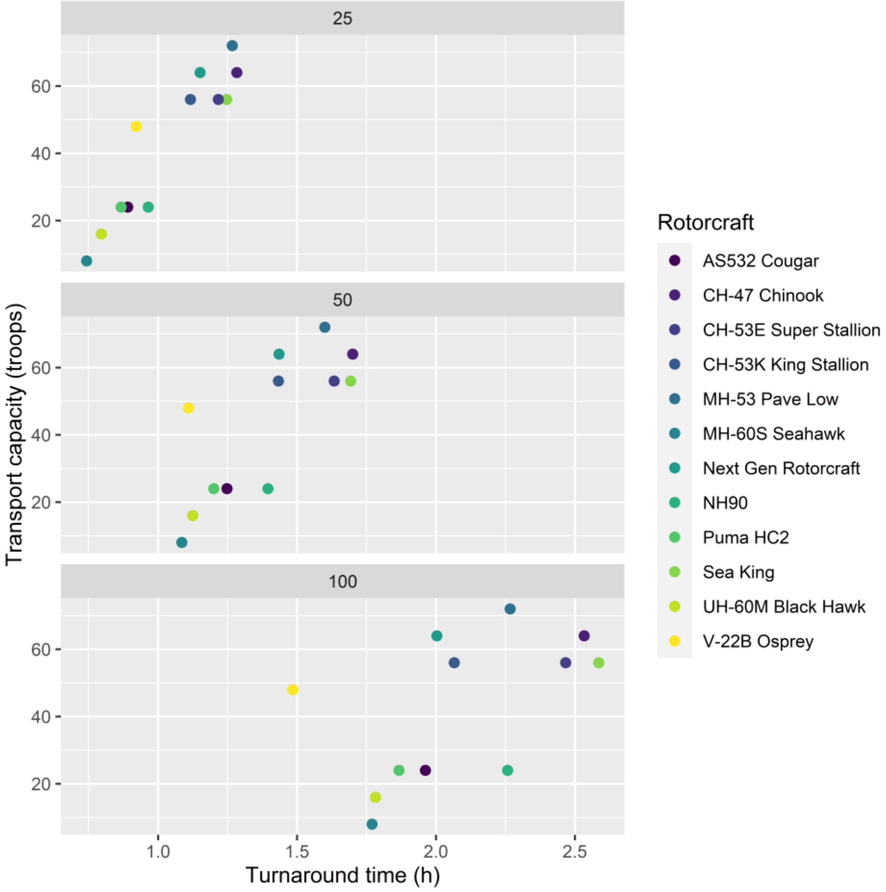


Figure 6 Wave characteristics of rotorcraft for a 25 nm, 50 nm and 100 nm distance to the objective area

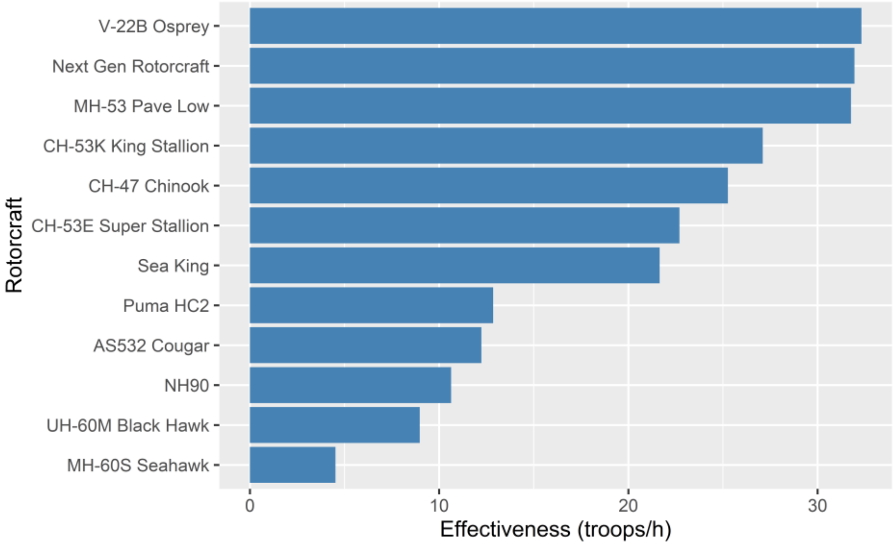


Figure 7 Rotorcraft effectiveness

Figure 8 V-22 Osprey Tilt Rotor Aircraft (Boeing, 2022)

3.3 Example 3: Operations Planning (Force Generation)

The ALM can also be used for operations planning, also known as force generation. Operations planning is planning the use of existing forces and capabilities for a known and existing contingency, or imminent contingency (Sartzis, 2019). An operations planner responsible for planning the amphibious landing can use the model to explore transport capacity (in number of troops) and completion time. In this example there is one amphibious ship carrying two landing craft of the same type and model. The landing craft can carry 20 troops at a speed of 20 kn. The ship-to-shore distance is 20 nm. Twenty troops need 20 min to embark or debark the connector. The waiting time on each leg of a round trip is 10 min. Table XIV shows the results for variations in (a) SUA, (b) number of waves, and (c) number of connectors that can be embarked and debarked at the same time.

Table XIV Operations planning

u	***f***	***m***	***n***	***w***	***v_unl*** kn	***v_loa*** kn	***dx*** nm	***dy*** nm	***t_alo2*** hh:mm	***n_emb***	***n_deb***	***margin_v*** kn
1	**40**	20	2	1	20	20	20	0	**03:00**	2	2	0
1	**40**	20	2	1	20	20	20	0	**03:40**	1	1	0
3	**36**	20	2	1	20	20	20	0	**02:56**	2	2	0
3	**36**	20	2	1	20	20	20	0	**03:32**	1	1	0
1	**80**	20	2	2	20	20	20	0	**06:00**	2	2	0
1	**80**	20	2	2	20	20	20	0	**07:20**	1	1	0
3	**72**	20	2	2	20	20	20	0	**05:52**	2	2	0
3	**72**	20	2	2	20	20	20	0	**07:04**	1	1	0

3.4 Example 4: Adaptability

“No plan of operations extends with any certainty beyond the first encounter with the main enemy forces.” – Helmuth von Moltke, 1871 (Quote Investigator, 2021). Suppose that when the amphibious ship of the previous example arrives at the scene, it becomes clear that one of the landing craft is unavailable because of engine failure. Table XV shows the original plan and how the engine failure affects the number of waves and completion time. Suppose that the amphibious landing must be completed in 10 hours. Table XV shows three alternative plans: (a) increase the connector speed to 26 kn, (b) reduce the ship-to-shore distance to 16 nm, and (c) reduce the number of waves to 3. Each alternative has a potential disadvantage. For example, even if the connector is capable of high speeds, an average speed of 26 kn may not be possible because of the weather conditions. Reducing the ship-to-shore distance may bring the amphibious ship within the effective range of weapons operated by enemy troops stationed on land. Reducing the number of waves reduces the transport capacity to 54 troops. If that alternative were chosen, the average speed can be reduced to 17 kn (as indicated by the value of *margin_v*) or the completion time is reduced to 8:48.

Table XV Adaptability

u	***f***	***m***	***n***	***w***	***v_unl***	***v_loa***	***dx***	***dy***	***t_alo2***	***n_emb***	***n_deb***	***margin_v***
					kn	kn	nm	nm	hh:mm			kn
3	**72**	20	2	2	20	20	20	0	**05:52**	2	2	0
3	72	20	1	**4**	20	20	20	0	**11:44**	1	1	0
3	72	20	1	**4**	**26**	**26**	20	0	10:00	1	1	0
3	72	20	1	**4**	20	20	**16**	**0**	10:00	1	1	0
3	**54**	20	1	**3**	20	20	20	0	10:00	1	1	3.3333
3	**54**	20	1	3	20	20	20	0	**08:48**	1	1	0

3.5 Example 5: Mixed Landing Cycles

The MLC can simulate the transportation of a homogeneous LF from one origin to different destinations, using connectors of different types and models (surface and/or air). In this example the LF consists of 400 troops. The LSD provides one LCU, two LCVPs and two helicopters to the amphibious landing. The helicopter is the Next Generation Rotorcraft of example 3. Tables XVI and XVII show the scenario data and connector data, respectively. Tables XVIII and XIX and Figure 9 show the simulation results.

Table XVI Scenario dataset

model	***atom***	***u***	***n***	***dx***	***dy***	***n_emb***	***n_deb***	***t_wfl***	***t_wrl***
				nm	nm			min	min
lcu	MIL	4	1	25	0	1	1	10	10
lcvp	MIL	4	2	50	0	2	2	10	10
next_gen_rotorcraft	MIL	4	2	100	0	2	2	10	10

Table XVII Connector dataset

type	***name***	***model***	***atom***	***m***	***v_unl***	***v_loa***	***t_emb_atom***	***t_deb_atom***
					kn	kn	min	min
LCU	LCU Mk10	lcu	MIL	120	10	8	0.25	0.25
LCU	LCU Mk10	lcu	CIV	160	10	8	0.5	0.5
LCVP	LCVP Mk5	lcvp	MIL	35	25	20	0.5	0.5
LCVP	LCVP Mk5	lcvp	CIV	46	25	20	1	1
Rotorcraft	Next Gen Rotorcraft	next_gen_rotorcraft	MIL	32	176	176	0.5	0.5
Rotorcraft	Next Gen Rotorcraft	next_gen_rotorcraft	CIV	42	176	176	1	1

Table XVIII Record of events

t2	***model***	***start_of***	***wave***	***n_origin***	***n_assigned***	***n_embarked***	***n_dest***
0:00	lcu	stop or go	0	400	0	0	0
0:00	lcu	embarkation	1	400	120	0	0
0:00	lcvp	stop or go	0	400	0	0	0
0:00	lcvp	embarkation	1	400	64	0	0
0:00	next_gen_rotorcraft	stop or go	0	400	0	0	0
0:00	next_gen_rotorcraft	embarkation	1	400	64	0	0
0:16	lcvp	transit loaded	1	336	0	64	0
0:16	next_gen_rotorcraft	transit loaded	1	272	0	64	0
0:30	lcu	transit loaded	1	152	0	120	0
1:00	next_gen_rotorcraft	debarkation	1	152	0	64	0
1:16	next_gen_rotorcraft	transit unloaded	1	152	0	0	64
2:00	next_gen_rotorcraft	stop or go	1	152	0	0	64
2:00	next_gen_rotorcraft	embarkation	2	152	64	0	64
2:16	next_gen_rotorcraft	transit loaded	2	88	0	64	64
2:56	lcvp	debarkation	1	88	0	64	0
3:00	next_gen_rotorcraft	debarkation	2	88	0	64	64
3:12	lcvp	transit unloaded	1	88	0	0	64
3:16	next_gen_rotorcraft	transit unloaded	2	88	0	0	128
3:48	lcu	debarkation	1	88	0	120	0
4:00	next_gen_rotorcraft	stop or go	2	88	0	0	128
4:00	next_gen_rotorcraft	embarkation	3	88	64	0	128
4:16	next_gen_rotorcraft	transit loaded	3	24	0	64	128
4:18	lcu	transit unloaded	1	24	0	0	120
5:00	next_gen_rotorcraft	debarkation	3	24	0	64	128
5:16	next_gen_rotorcraft	transit unloaded	3	24	0	0	192
5:22	lcvp	stop or go	1	24	0	0	64
5:22	lcvp	embarkation	2	24	24	0	64
5:38	lcvp	transit loaded	2	0	0	24	64
6:01	next_gen_rotorcraft	stop or go	3	0	0	0	192
6:01	next_gen_rotorcraft	stop	3	0	0	0	192
6:58	lcu	stop or go	1	0	0	0	120
6:58	lcu	stop	1	0	0	0	120
8:18	lcvp	debarkation	2	0	0	24	64
8:34	lcvp	transit unloaded	2	0	0	0	88
10:44	lcvp	stop or go	2	0	0	0	88
10:44	lcvp	stop	2	0	0	0	88

Table XIX Summary of the record of events

model	***t2***	***n_waves***	***n_atoms***
lcu	6:58	1	120
lcvp	10:44	2	88
next_gen_rotorcraft	6:01	3	192

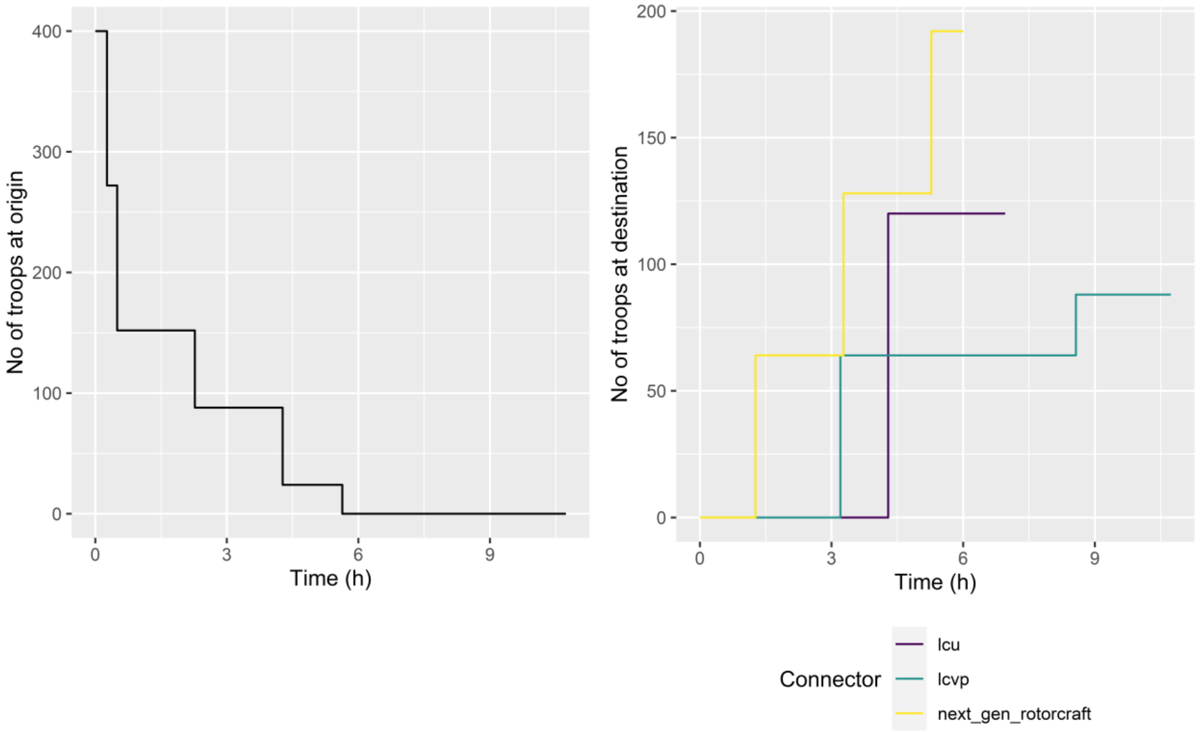


Figure 9 Mixed landing cycles

3.6 Example 6: Evacuation of Non-combatants

The MLC can also simulate a NEO. This example differs from the previous example in four ways: (a) the amphibious landing is an extraction operation: there are 1,000 non-combatants assembled at an area on land near the coast; (b) there is a casualty rate of two non-combatants per hour; (c) the operation cannot start earlier than 50 hours after receiving the order to evacuate; and (d) the connector payload capacity is larger: it is assumed that more people will board the connector than what is considered to be safe in normal situations. It is assumed that the Next Generation Rotorcraft can carry 42 non-combatants (floor loaded). Table XX and Figure 10 show the simulation results. Note that each line in the destination plot of Figure 10 ends with a vertical segment (Figure 9: horizontal segment) because it is an extraction operation.

Table XX Evacuation of non-combatants

model	***t2***	***n_waves***	***n_atoms***
lcu	58:15	2	320
lcvp	56:57	3	276
next_gen_rotorcraft	57:10	4	293

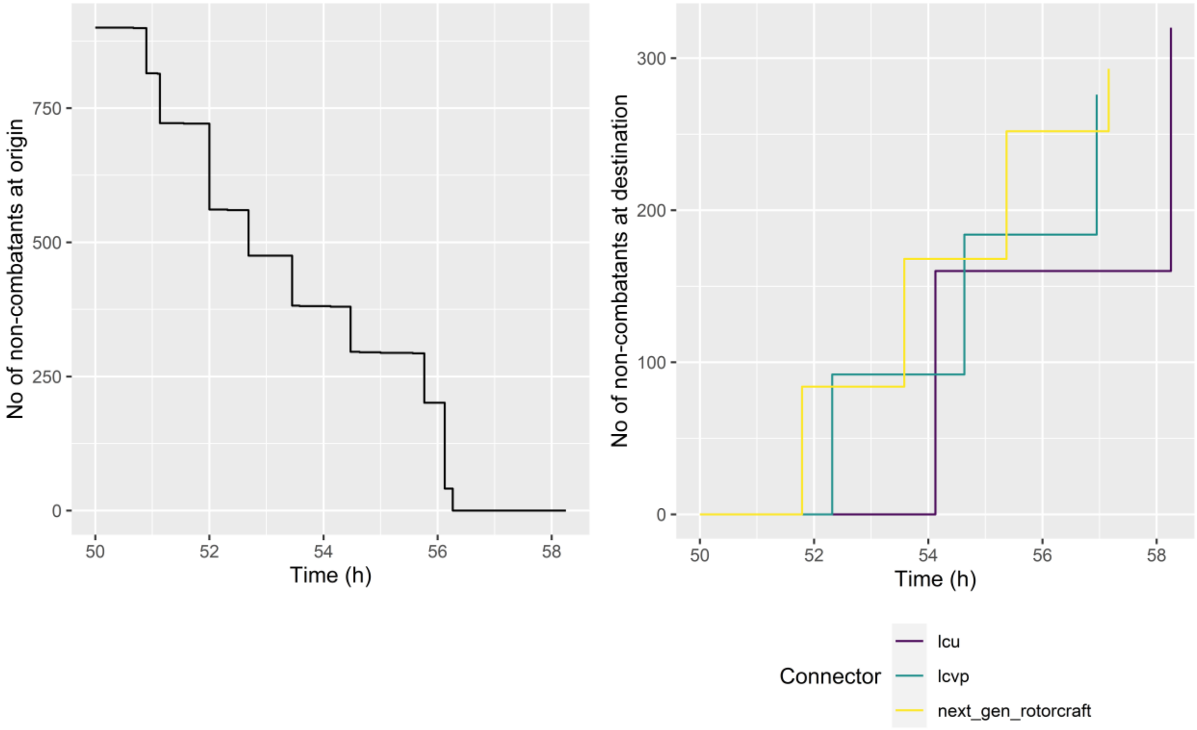


Figure 10 Evacuation of non-combatants

4 Conclusion

Designing effective amphibious ships and connectors starts with analysing the amphibious landing: the transportation of the landing force from the amphibious task group to the beach. The analytical tool presented in this paper allows the user to simulate the amphibious landing. It can provide understanding, insight, and knowledge that are critically important to the design of an effective amphibious warfare capability.

The analytical tool is intended to be used early in the design process. Its purpose is to support the user to find an acceptable balance between the different factors that determine the operational effectiveness of the amphibious landing. The tool is based on a set of analytical equations and is capable of solving these for any combination of two factors or variables.

There is a need for this tool because amphibious operation requirements are often conflicting – for example ship-to-shore distance and time – which makes it difficult to find an acceptable balance between operational effectiveness, technical feasibility and affordability. Technical feasibility and affordability are not part of the analysis, but can be included in the results without great difficulty.

Typical applications of the tool are: defence planning, comparing and contrasting the effectiveness of different connector types and models, operations planning (force generation), adaptability, and evacuating non-combatants (NEO).

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Appendix A Equations

Equation 1: transport capacity

$$\text{ceiling}\left(\frac{f}{m' \cdot n}\right) = w$$

Equation 2: transport speed

$$\text{floor}\left(\frac{v \cdot t}{2d}\right) = w$$

Size of landing force unit

$$U = \{1, 2, 3, \ldots, m\}$$

$$V = \text{elements of } U \text{ for which Equation 1 holds}$$

$$W = \text{elements of } V \text{ for which } f = m' \cdot n \cdot w \text{ is maximum}$$

$$u = \max(W)$$

Size of landing force

$$f = m' \cdot n \cdot w$$

Connector payload capacity

$$m = \text{ceiling}\left(\frac{y}{n}\right) \cdot u$$

Number of connectors

$$n = \text{ceiling}\left(\frac{y}{\mathrm{z}}\right)$$

Number of waves

$$w = \text{ceiling}\left(\frac{\mathrm{x}}{z \cdot n}\right)$$

Number of waves

$$w = \text{floor}\left(\frac{v \cdot t}{2d}\right)$$

Average speed of connector

$$v = \frac{2d \cdot w}{t}$$

Ship-to-shore distance

$$d = \frac{v \cdot t}{2w}$$

Transit time

$$t = \frac{2d \cdot w}{v}$$

where

$$x = \text{ceiling}\left(\frac{f}{u}\right)$$

$$y = \text{ceiling}\left(\frac{x}{w}\right)$$

$$z = \text{floor}\left(\frac{m}{u}\right)$$

$$m' = z \cdot u$$

The function ceiling rounds a number up to the nearest integer; the function floor rounds a number down to the nearest integer.

Appendix B Specifications of military off-the-shelf rotorcraft

Manufacturer	Name	Variant	Capacity floor loaded	Capacity seated	Maximum speed	Cruise speed	Range	Combat range
					kn	kn	nm	nm
Eurocopter	AS532 Cougar	AS532 U2	16	12	170	140	432	144
Boeing	CH-47 Chinook	CH-47F	57	33	170	120	400	200
Sikorsky	CH-53E Super Stallion	CH-53E	55	30	150	120	540	180
Sikorsky	CH-53K King Stallion	CH-53K	55	30	170	158	460	110
Sikorsky	MH-53 Pave Low	MH-53J	55	37	170	150	600	200
Sikorsky	MH-60S Seahawk	MH-60S	6	5	180	146	450	245
NHIndustries	NH90	NH90 TNFH	18	14	140	116	432	144
Airbus Helicopters	Puma HC2	HC Mk2	16	12	167	150	939	313
Westland	Sea King	HC.4	37	28	124	112	664	221
Sikorsky	UH-60M Black Hawk	UH-60M	14	11	159	152	960	320
Bell-Boeing	V-22B Osprey Tilt Rotor Aircraft	MV-22B	32	24	280	266	879	430

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www.lockheedmartin.com
www.bellflight.com
en.wikipedia.org

Data without reference have been created from the following assumptions:

- CH-53K King Stallion: capacity floor loaded = capacity floor loaded CH-53E Super Stallion
- Other rotorcraft: capacity floor loaded = floor(capacity seated × (4 / 3))
- Maximum speed = cruise speed / 0.9
- Cruise speed = maximum speed × 0.9
- Range = combat range × 3
- Combat range = range / 3

The combat range is the maximum distance from the base (i.e., the amphibious ship) assuming that one-third of fuel is used for the outward journey, one-third of fuel is used for combat operations, and one-third of fuel is used for the return journey.