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LOCK CAPACITY AND TRAFFIC RESISTANCE OF LOCKS

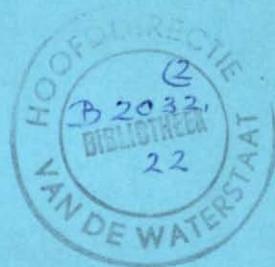
BY

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Summary

Lock capacity and traffic resistance are factors which play an important part in the assessment of future traffic through existing locks and in the determination of the number and size of new ones. In this context lock capacity means the maximum quantity of shipping which can be locked per unit of time in the prevailing conditions, if a lock is operating continuously with full chamber(s). The resistance is reflected in the time lost by shipping due to locking.

The present publication deals with methods of determining lock capacity and resistance. The methods relate to cargo-carrying inland waterway vessels of the type operating on Western European waterways.

For the purposes of the computations vessels have been subdivided into eight deadweight tonnage categories. A representative standard ship has been selected for each category, the greatest possible degree of uniformity with the ECMT classification having been sought. An extensive enquiry into the vessel mix showed there to be a reasonably close connection between the frequency distribution of deadweight tonnage categories and the average deadweight tonnage of the vessels. The average deadweight tonnage has therefore been employed as a quantity which is characteristic of the vessels in a particular category.

The lock capacity is determined by the maximum number of vessels per lockage and the lockage time. The maximum number of vessels that a lock chamber can hold has been determined for a large number of lock sizes by simulations of vessel distribution within locks. The results have been checked against actual observations.

The locking time has been subdivided into the vessel entry and exit times on the one hand, and the operating time on the other. The entry and exit times of both laden and unladen standard vessels have been determined as a function of the average deadweight tonnage and the wetted cross-section at the lock gate on the basis of a very large number of observations at approx. 30 different lock chambers. Only a few observation results have been reported with regard to operating times.

Detailed instructions are then given for the computation of the capacity of a lock chamber. The method of computation is checked by comparing the computed and measured capacities of a number of existing locks.

The resistance of a lock is equal to the average total transit time of the individual vessel. The transit time begins at the moment when the vessel arrives at the lock and ends at the moment the vessel has left the lock. It consists of two parts. The first part relates to all vessels to be locked and is equal to the normal waiting time plus the lockage time. The second part is the delay time, which only arises if, at a time of high traffic

volume, a vessel has to miss one or more lockages after arrival before its turn comes round.

Equations have been derived for the determination of both waiting and lockage times. Delay time is dependent on the level of traffic volume, the arrival pattern of vessels (volume pattern) and the lock capacity. It is determined by means of a simulation of the locking process, this simulation being carried out on a weekly basis. Volume patterns based on observations at existing locks are taken as the starting point. A method is given for working out such patterns.

From a number of locking simulations is obtained what is known as the delay curve, which shows the relation between the average delay time per vessel and the traffic volume/capacity ratio on a weekly basis.

The delay time is strongly influenced by variations in traffic volume. The volume pattern is therefore characterised by using a variation coefficient which is equal to the quotient of the standard deviation of the hourly volumes and the average hourly volume. For a constant weekly volume an increasing value of the variation coefficient results in a lengthening delay time.

In the last chapter the methods of computation are applied to several specific cases. The results provide an insight into the relation between lock dimensions and capacity, the effect of a number of locks on the transit time, etc.

The concept of 'admissible annual volume' is also introduced in this chapter. It indicates the quantity of shipping that can be handled by the lock per year without unacceptably long waiting periods arising. The admissible annual volume depends on the lock capacity, the volume pattern and the seasonal fluctuations in traffic.

1. General observations

1.1 Introduction

In the past, when traffic on the inland waterways was far less heavy than it is today, the size of the largest vessel to be admitted to a waterway was one of the most important factors considered when deciding on the dimensions of a lock. The duration of a lockage was only of secondary importance since the turn-round times were long in any case because of the low navigation speeds and the length of time required for loading and unloading.

The rapid increase in traffic volume, particularly since the beginning of the fifties, and in several waterways even before that time, led to lock capacity becoming an important factor in the handling of traffic on canals and canalised rivers. New locks therefore were as far as possible designed to enable the locking process to proceed as efficiently as possible. The principal measurements of the lock chamber were so chosen as to allow various combinations of the commonest types of vessel to be handled in a single lockage.

However, there were no adequate methods of calculation available for determining in advance the capacity of a new lock. Frequently the capacity was estimated on the basis of experience with existing locks. This led to excessive emphasis being placed on the relationship between the capacity and the surface area of the lock in the sense that the available number of square metres was considered to be one of the most important factors affecting the situation.

During the sixties various attempts were made, both in the Netherlands and elsewhere, to devise methods of calculation based on an analysis of the locking process. Examples of foreign studies in this field will be found in the Bibliography (Nos. 1 and 2). The Dutch studies related primarily to special cases, such as for example locks for push-tows. The results of the various studies are not, however, suitable for general application.

A powerful impetus was given to the establishment of more generally applicable methods of calculation when the preparation of a routing model of the waterway network in the Netherlands was begun in 1970 by the Netherlands Institute of Transport. The purpose of this routing model was to enable the best possible forecasts to be given of future traffic volumes on waterways in the Netherlands. The traffic data for the construction and operation of the model had largely to be supplied by 'Rijkswaterstaat'. For this purpose a number of studies were carried out, whose results, insofar as they relate to the capacity and resistance of waterway components, have been published in a very abridged form (see Bibliography Nos. 3 and 4).

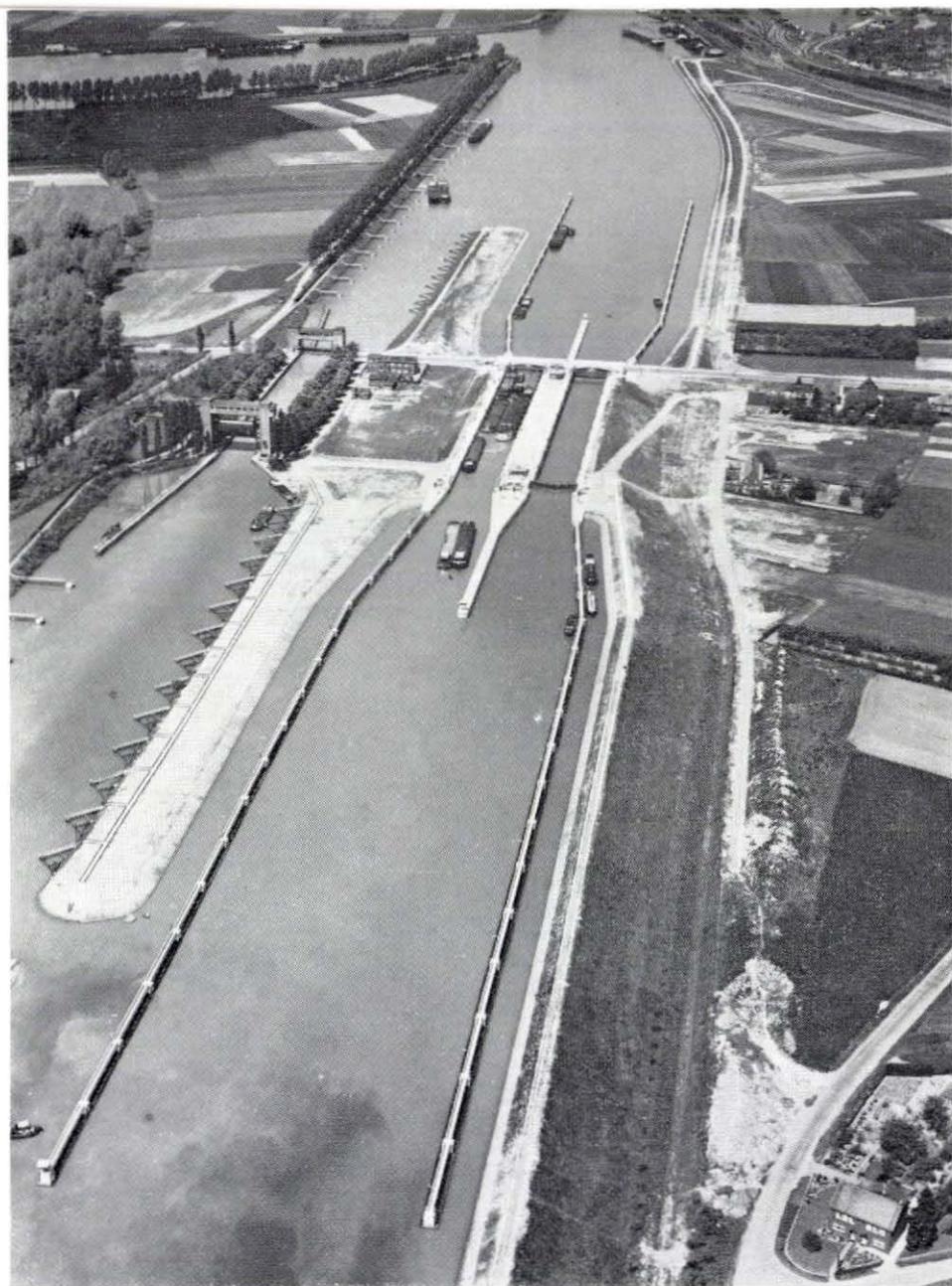


Photo 1. Example of a modern lock (at Born, Juliana Canal, location Figure 5, No. 21).

The methods of calculation which were devised in connection with the routing model for the determination of the capacities of locks and the delay experienced by vessels in passing through them, have been further developed and refined and are dealt with exhaustively in the present publication. The latter also contains a considerable amount of data enabling the aforementioned methods of calculation to be used to arrive at a reasonable approximation of the resistance and capacity of a lock which is being designed. Since, however, the calculation models to be applied contain several schematic representations of the actual situation, it must always be remembered that there may be divergencies in practice.

Finally, it must be pointed out that further research will be necessary to improve the calculation models. In the view of those compiling this publication every effort should be made to take into account as far as possible the stochastic nature of the locking process.

1.2 Scope

From a navigational point of view three factors are of decisive importance in the drawing up of the design specifications for a new lock. These factors are as follows:

1. the dimensions of the largest vessel to be admitted.
2. the lock capacity.
3. the transit time per vessel.

The minimum principal dimensions of the lock chamber are determined by the maximum size of vessel referred to in 1. For self propelled inland waterway vessels and push tows these can generally be taken to be as follows:

Effective chamber length = 1.10 times length of vessel
Chamber width = 1.05 times length of vessel
Depth of water above sill = 1.4 to 1.5 times the draught.

(Note: if the maximum size of vessel only occurs sporadically, 1.3 times the draught will be sufficient).

From the requirements which the lock must meet with regard to lock capacity and the transit time of vessels can be concluded whether the dimensions of the chamber must be larger than the minimum and also whether two or more parallel chambers will have to be built.

Methods of calculation are developed in the following chapters to enable the lock capacity and the transit time of the individual vessel to be determined for any given lock. The data required to apply the methods of calculation are contained in Appendices 1, 2 and 3. A fully worked out example is provided in Appendix 4.

The last chapter deals with a number of practical applications which may be of use in the design of locks.

Although the methods of calculation developed relate to locks of modern design and construction (see Section 4.1), they are only applicable to inland waterway locks used primarily for commercial navigation (see Chapter 3) and situated on waterways in the Netherlands and possibly elsewhere in Western Europe. This means among other things that locks for sea-going vessels and locks built specially for pleasure traffic have been disregarded. The same applies to flights of locks, which are not found in the Netherlands.

The use of split chambers in locks which are provided with intermediate gates is not dealt with separately. However, calculation of lock capacity and transit times is indeed possible using the methods dealt with, if allowance is made for the special circumstances obtaining in the case of locks with split chambers.

Finally, it should be noted that the methods of calculation can also be applied to the many old locks to be found on waterways in the Netherlands. In that event, however, it is necessary to use adjusted values for vessel entry and exit times when calculating the locking cycle time.

1.3 Notation

The following symbols have been used:

A_l	switch distance	(m)
A_{t1}	number of vessels to be locked in hour t in direction 1	
B	navigable width of lock gate passage	(m)
B_k	width of lock chamber (modern lock $B_k = B$)	(m)
C_s	lock capacity	(VPH)
C_{sr}	lock capacity in one direction	(VPH)
C_T	lock capacity	(TPH)
C_{Tr}	lock capacity in one direction	(TPH)
C_w	lock capacity per week (vessels per week)	
CV	coefficient of variation of weekly traffic volume	
D	depth of water above the sill or the floor at the lock gate	(m)
D_l	ditto at the lower gate	(m)
D_u	ditto at the upper gate	(m)
F	surface of wetted cross-section above the sill or the floor at the lock gate	(sq.m.)
F_l	ditto lower gate	(sq.m.)
F_u	ditto upper gate	(sq.m.)
H	lift	(m)
I	traffic volume	(VPH)
I_a	maximum admissible annual volume of traffic in deadweight tons per year	
I_o	annual volume of traffic in deadweight tons per year	

I_w	weekly volume of traffic in vessels per week	
I_{t1}	volume of traffic in hour t in direction 1	(VPH)
L	effective length of lock chamber	(m)
N	number of (parallel) chambers per lock	
O_t	number of delay hours in hour t	
S	standard deviation	
VPH	vessels per hour	
T	deadweight tonnage of a vessel	(metric tons)
T_b	operating time of the lock	(min.)
T_c	duration of the locking cycle	(min.)
T_d	duration of a lockage	(min.)
T_i	time taken for all vessels to enter the lock	(min.)
T_s	deadweight tonnage of standard class s vessel	(metric tons)
T_u	time taken for all vessels to leave lock	(min.)
TPH	deadweight tonnage per hour	
b .	beam of vessel	(m)
f .	area of wetted cross-section of the vessel	(sq.m.)
l	length of vessel	(m)
n	number of vessels in the lock chamber	
n_{max}	maximum number of vessels the lock chamber can hold	
p_s	probability of occurrence of standard vessel s	
s	denotes standard vessel class	
t_i	entry interval	(min.)
t_l	switch interval	(min.)
t_o	delay time	(hours)
t_p	total transit time of a vessel	(min. or hours)
t_s	lockage time of one vessel	(min.)
t_u	exit interval	(min.)
t_w	waiting time of a vessel	(min.)
z	number of lockages in a selected period	
λ	ratio of the number of laden vessels to the total number of vessels	

Note: the average value of a variable is indicated by a bar (—) over the symbol.

2. The most important aspects of the locking process

2.1 Locking cycle

The locking process can be looked at from the point of view of the lock operator and from that of the waterway user. As the lock operator is concerned with a series of operations which are continually repeated, there can be said to be a cyclical process. The individual waterway user is only involved in part of the locking cycle. For him, passage through a lock consists primarily of waiting. The total transit time, which will be gone into further in Section 2.3, is the most important aspect for the waterway user.

For the purposes of a closer examination of the locking cycle a distinction must be made between one-way and two-way locks. Two-way traffic applies in far and away the greater number of cases. One-way traffic is only possible if a lock has two or more parallel chambers and, even then, it is only employed in practice on very rare occasions.

The locking cycle for two-way traffic is shown schematically in Figure 1. It consists of two consecutive locking operations:

$$T_c = T_d \text{ (upstream)} + T_d \text{ (downstream)} \quad (1)$$

The duration of the lockage (T_d) is made up of three parts: the total entry time (T_i), the operating time (T_b) and the total exit time (T_u).

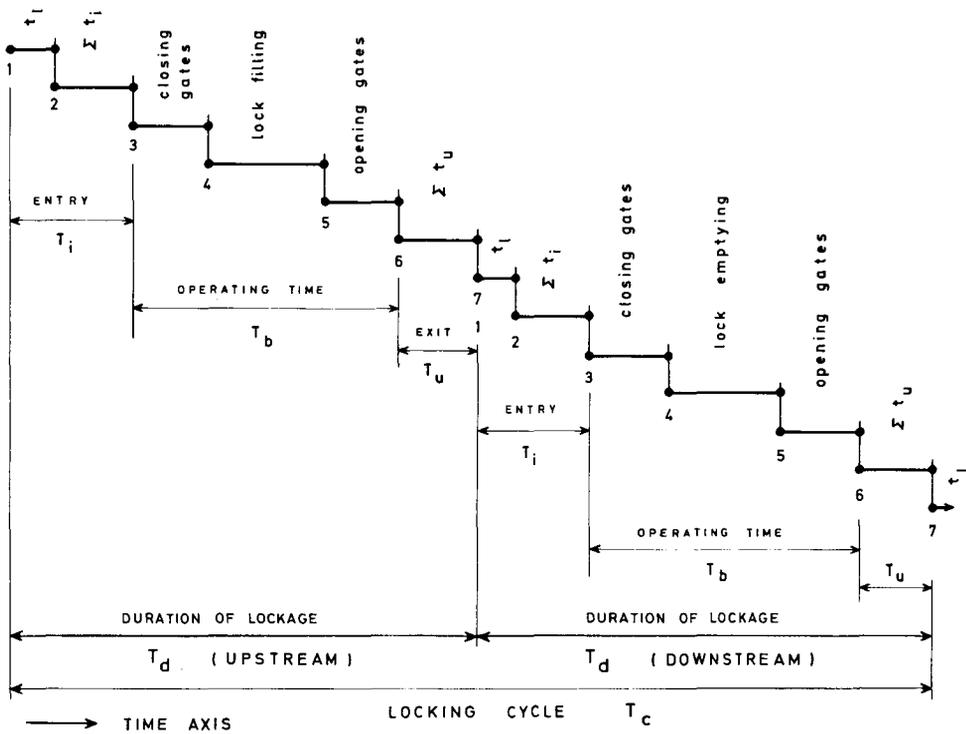
$$T_d = T_i + T_b + T_u \quad (2)$$

As can be seen from Figure 1, entry is considered to commence at the moment when the stern of the last vessel leaving after the previous lockage passes the lock gates. Entry is divided into two parts, namely the switch interval (t_i) and the sum of the entry intervals (Σt_i):

$$T_i = t_i + \Sigma t_i \quad (i = 2, \dots, n) \quad (3)$$

The switch interval is determined by both the vessel which is leaving and the one which is entering. The vessel leaving must have proceeded far enough for the way to be clear for the first vessel entering.

The operating time (T_b) begins at the moment when the entry of the last vessel of the lockage has been completed and ends when the gates on the exit side have been opened



LEGENDS

Point of time.

1. stern of vessel of previous lockage passes gates.
2. Stern of first vessel to enter passes gates.
3. Stern of last vessel to enter passes gates.
4. Entry gates closed
5. Exit gates start opening.
6. Exit gates open (first vessel starts leaving).
7. Stern of last vessel leaving passes gates.

Symbols.

- t_j : switch interval
(interval between exit of last vessel of preceding locking operation and completed entry of first vessel of new locking operation).
- t_i : entry interval
(interval between completed entries of successive vessels).
- t_u : exit interval
(interval between completed exits of successive vessels).

Figure 1. Basic elements of the locking cycle.

after the chamber has been filled or emptied and the first vessel can start to leave the lock.

Total exit time (T_u) is equal to the exit time of the first vessel plus the sum of the exit

intervals of the remaining vessels. As, however, the exit time of the first vessel does not differ significantly from the exit interval (t_u) of a similar vessel, for simplicity the same symbol is used:

$$T_u = \sum t_u \quad (u = 1, \dots, n) \quad (4)$$

In the case of one-way traffic a lockage with vessels is always followed by a dummy lockage in the opposite direction. The equation (2) applies to the locking direction. In the case of the dummy lockage the duration of the lockage $T_d = T_b$.

2.2 Lock capacity

If the lock chamber is completely filled with vessels in successive lockages and no particular delays occur during operation of the lock or during entry and exit, the maximum amount of traffic is being handled. In other words the lock capacity has been reached.

Even when the chambers are full the number of vessels per lockage will generally depend on the vessel mix and the order of arrival of vessels. The result of this is that neither the maximum number of vessels handled per locking cycle nor the duration of the locking cycle itself are constant. To avoid confusion the lock capacity is therefore related to a fixed unit of time and defined as follows:

The capacity of a lock is the maximum amount of traffic, expressed in numbers of vessels or deadweight tons, that can be locked per unit of time in the prevailing conditions if the lock operates continuously with full chamber(s).

The various elements in this definition are further explained as follows:

- a. The definition means that the capacity is an average value derived from a large number of lockages with full chambers.
- b. A particular capacity only applies in the conditions prevailing. These include:
 - the vessel mix as regards type, size vessel utilisation (λ), etc.
 - the operating conditions at the lock with regard to the quality and number of personnel etc.
 - the time of day (daylight or darkness).
 - the weather conditions.

For simplicity, the hour has been taken as the unit of time for calculation of the lock capacity. In the case of two-way traffic, the following equations hold good for the capacity in vessels per hour (C_s) and deadweight tons per hour (C_T):

$$C_s = \frac{2n_{\max}}{T_c} \times 60 \text{ in VPH} \quad (5)$$

$$C_T = C_s \times \bar{T} \quad \text{in TPH} \quad (6)$$

In these equations n_{\max} and T_c are average values of the number of vessels and the cycle times (in minutes) respectively of a large number of lockages with a full chamber; \bar{T} is the average deadweight tonnage per vessel.

In practice the special case may arise that, while in one direction the volume of traffic is so great that the lock is continually being operated with full chambers, there is only a small amount of traffic in the other direction, with the result that the lock is operating with its chambers only partly full of vessels. According to the definition just given the lock capacity is not then reached. Because, however, the lock is being operated continuously with full chambers in one direction, it is permissible in that event to work with a capacity per direction of navigation (C_{sr} and C_{Tr}) which is determined as follows:

$$C_{sr} = \frac{n_{\max}}{T_c} \times 60 \quad (7)$$

The capacity per direction of navigation is not constant but depends on the number of vessels that are locked in the opposite direction. If this number declines, C_{sr} increases.

Equation (7) is also applicable to a lock chamber handling traffic in one direction.

2.3 The transit time of the individual vessel

The transit time is defined as follows:

The transit time of the individual vessel (t_p) is equal to the total extra time required by a lockage compared with an imaginary situation in which there was no lock and the vessel could proceed at cruising speed.

The transit time is made up of three parts:

$$t_p = t_w + t_s + t_o \quad (8)$$

in which:

t_w = waiting time

t_s = locking time

t_o = delay time (the additional waiting time that arises if the vessel arriving at the lock cannot be included in the first lockage because the chamber is already full).

The importance of the various parts of the transit time can be seen from Figure 2 in which the lockage of a number of vessels is shown in schematic form, using a time-

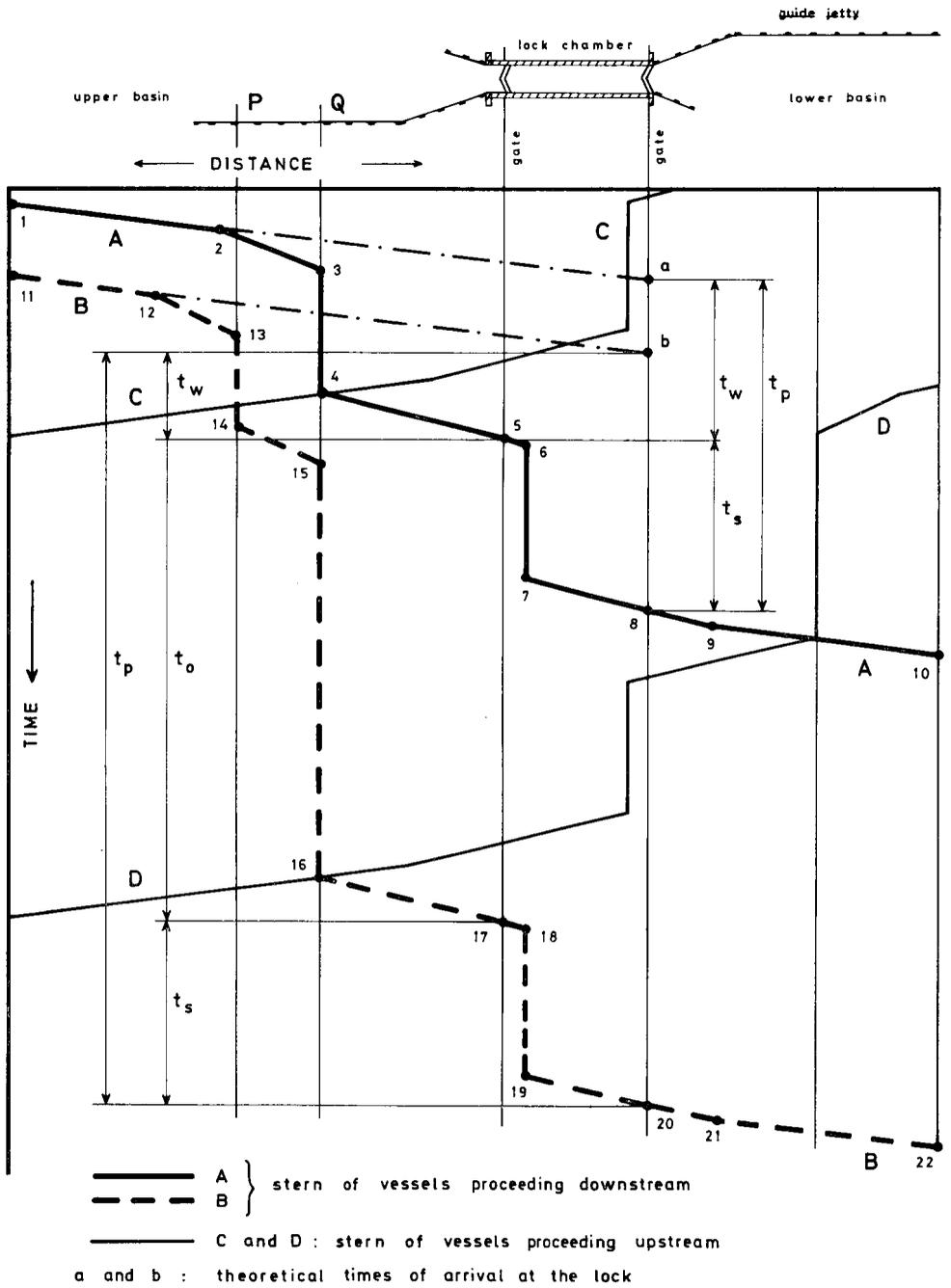


Figure 2. Time-distance diagram showing transit through lock.

distance diagram. For simplicity, this has been based on a lock chamber which can only hold a single vessel.

Vessels A and B proceeding downstream arrive at the lock while vessel C, proceeding in the opposite direction, is being locked. A can be locked after the exit of C ($t_p = t_w + t_s, t_o = 0$). B has to wait a complete lock cycle ($t_p = t_w + t_s + t_o$).

The following phases are to be distinguished in Figure 2 with regard to the passage of vessel A through the lock.

- 1-2 cruising speed
- 2-3 reducing speed and stopping
- 3-4 waiting in lay-by Q
- 4 vessel C completes transit
- 4-5 entry into lock
- 5-6-7 operating time (T_b)
- 7-8 exit from lock
- 8-9 accelerating
- 9-10 cruising speed

In the further steps it is assumed that after leaving the lock (point 8 for vessel A) the vessel immediately proceeds at cruising speed; this simplification is justified because it only involves a very slight difference in time. It means that the transit time is regarded as ending at the moment when the stern passes the lock gates during exit from the lock. The theoretical beginning of the transit time coincides with the moment when the stern would have reached the aforementioned position if the vessel had been able to proceed at cruising speed without having to be locked. For vessel A this is point a.

It can be stated on the basis of the foregoing that:

- t_p runs from a to 8,
- t_w from a to 5 and
- t_s from 5 to 8.

The phases for vessel B are identical with those of vessel A with the proviso that in phase 14-15 it is moved up from lay-by P to Q. The theoretical moment of arrival is at point b.

The following is true of vessel B:

- t_p runs from b to 20
- t_w runs from b to 5 (as in the case of vessel A)
- t_o runs from 5 to 17 ($= T_c$)
- t_s runs from 17 to 20.

3. Characteristics of vessels on the inland waterways

3.1 The vessel mix

Vessels can be classified in several different ways on the basis of their functions and characteristics. To obtain an idea of their importance from the point of view of the handling of traffic at locks, several methods of classification will be subjected to a closer examination.

PROFESSIONAL NAVIGATION — PLEASURE CRUISING

Professional navigation is practised by people who are on the waterways by virtue of their occupations. In this context, therefore, professional navigation does not only relate to the transport of goods and passengers but also includes navigation involving such vessels as patrol boats, floating derricks, dredgers etc.

Pleasure cruising is exclusively recreational in character.

In contrast with professional navigation, pleasure cruising, at least in Europe, is very closely associated with the summer season (the period from May to September). Outside the holiday period, which broadly speaking runs from the middle of June to the middle of August, pleasure cruising is mainly confined to weekends. Professional navigation takes place primarily on weekdays (including Saturday).

The proportion of total traffic accounted for by pleasure cruising varies from one waterway to another, as will be seen from the observation results recorded in Table 3.1.1.

Finally, it should be noted that the space occupied by a pleasure craft in a lock chamber amounts to only a fraction of that taken up by the average vessel engaged in professional navigation.

The position just outlined shows that, generally speaking, pleasure cruising does not play a very important part in the volume of traffic handled by locks except in the holiday season, and even then it does so only in the case of a limited number of locks. For the time being, therefore, pleasure cruising is only taken into account indirectly, by the application of corrections to calculated figures.

Since, however, the volume of pleasure cruising is rapidly increasing it would be worth while subjecting the compatibility of professional navigation and pleasure cruising to closer examination.

Monitoring point (see fig. 5)	Total number of vessels	Pleasure craft	
		Number	%
1	28,500	4,300	15.0
2	79,400	16,400	20.7
5	57,000	1,800	3.2
8	33,700	1,900	5.6
12	135,600	11,700	8.6
14	99,200	<1,000	<1.0
19	27,300	<1,000	<3.0
20	81,200	2,200	2.7

Table 3.1.1 Proportion of total shipping accounted for by pleasure cruising in 1972 (Source Bib. [5]).

CARGO VESSELS FOR INLAND NAVIGATION — OTHER TYPES OF PROFESSIONAL SHIPPING

A distinction can be drawn between vessels designed to carry dry or liquid cargoes and other types of shipping. The latter category is composed of vessels with widely differing functions, as for example tugs without barges, fishing vessels, passenger vessels, patrol boats etc.

On the majority of waterways the category represented by other types of shipping constitutes only a small percentage of all professional shipping. Such shipping is therefore disregarded in the further treatment of the capacity and resistance of locks.

SELF-PROPELLED INLAND WATERWAY VESSELS — TOWED BARGES

Inland waterway fleets in Western Europe have been largely motorised during the past decade. New vessels built have been almost exclusively motor vessels, while in addition many towed barges have been taken out of commission or provided with their own means of propulsion.

Push-towing, which has been developed since the second half of the fifties, has many similarities with motorised shipping as far as handling qualities are concerned. Push-tow units are therefore included in the category of self-propelled vessels.

Table 3.1.2 shows that the proportion of towed barges is very small. A further decline in pull-towing is very probable in view of the developments in the last few years.

Monitoring point (see fig. 5)	Total number	Towed barges	
		Number	%
1	22,930	540	2.3
2	55,600	3,740	6.6
5	52,250	2,170	4.3
8	30,120	1,570	5.2
12	116,310	2,460	2.1
14	94,310	2,000	2.1
19	27,170	90	0.3
20	73,470	5,670	7.7

Table 3.1.2 Proportion of cargo vessel category accounted for by pull-towing in 1972 (Source Bib. [5]).

3.2 Deadweight tonnage categories and standard vessels

As stated in Section 3.1, the further investigation into the resistance and capacity of locks will be based on cargo vessels for inland navigation. The smallest of such vessels are less than 100 deadweight tons. The largest are push-tow units consisting of a combination of a pusher-tug and four barges, whose total deadweight tonnage can be in the region of 10,000 tons. Between these two extremes there is a wide variety of deadweight tonnages (see Appendix I, fig. 1).

To make the shipping traffic problem amenable to the carrying out of calculations, inland waterway vessels have been subdivided into deadweight tonnage categories. A representative standard vessel has been chosen for each category, the greatest possible degree of uniformity being sought with the ECMT (European Conference of Ministers of Transport) system of classification.

The limits of the deadweight tonnage categories and the standard vessel data are given in Table 3.2.1. More detailed information is contained in Table 1 of Appendix I.

An exhaustive investigation has been carried out into the proportion of inland waterway vessels accounted for by each deadweight tonnage category. For this purpose, observations were made at a large number of points on the waterway network throughout the country. From the results of the observations it was possible to derive quite a close relation between the average deadweight tonnage of the vessels (\bar{T}) and the frequency distribution of the deadweight tonnage categories (figure 3).

Grateful use has been made of the results of this investigation to ascertain the proportion of vessels by deadweight tonnage categories at a given point on the waterway network, to be characterised by using \bar{T} as a parameter. This parameter also plays an

No.	Deadweight tonnage category (metric tons)	Standard vessel data			
		Deadweight tonnage (metric tons)	Length (m)	Beam (m)	Draught (m)
0	50- 199	125	25	4.6	1.6
1	200- 449	325	39	5.1	2.3
2	450- 749	550	50	6.6	2.5
3	750-1,149	925	67	8.2	2.5
4	1,150-1,549	1,350	80	9.5	2.6
5	1,550-2,549	2,000	95	11.5	2.7
6	2,550-4,999	4,100	175	11.4	3.0
7	>5,000	8,800	185	22.8	3.2

Table 3.2.1 Classification of deadweight tonnage categories and standard vessels.

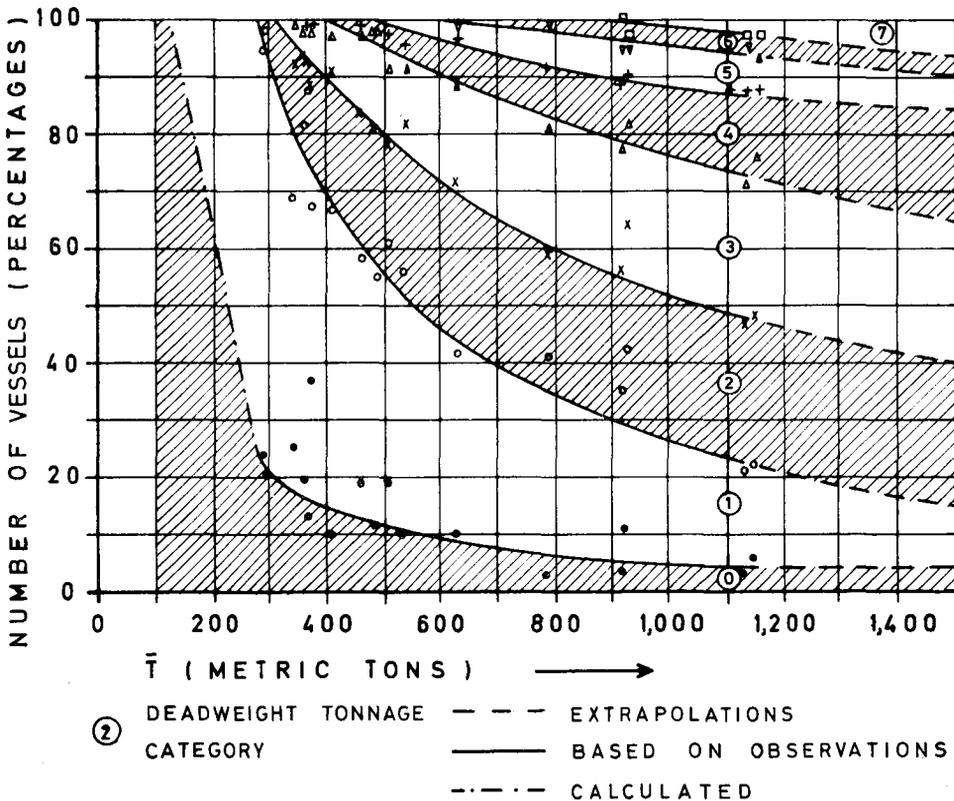


Figure 3. The relative proportions of the deadweight tonnage categories as a function of the average deadweight tonnage (\bar{T}).

important role in another respect, in that the relevant values relating to the locking process, as for example the average entry and exit times of vessels, the maximum number of vessels in the chamber and the lock capacity are expressed as a function of \bar{T} . By using Figure 3, an analysis of the vessels can be prepared for a selected value of \bar{T} by substituting the representative standard vessels (Table 3.2.2) for the deadweight tonnage categories.

\bar{T} (tons)	Proportion of standard vessels (%)						
	0	1	2	3	4	5	6
300	20.0	73.0	7.0	—	—	—	—
500	12.0	43.4	26.1	13.0	4.6	0.9	—

Table 3.2.2 The composition of a schematised vessel mix for given values of \bar{T} .

The standard frequency distribution of the standard vessels which have been used in a large number of calculations are given in Table 2 of Appendix I for several navigability classes. A characteristic of all distributions is that $\bar{T} = \sum p_s T_s$, where T_s is the deadweight tonnage of class s standard vessel, and p_s is the proportion of the class s vessels in the vessel mix.

Example: $\bar{T} = p_0 T_0 + p_1 T_1 + p_2 T_2$
 $300 = 0.20 \times 125 + 0.73 \times 325 + 0.07 \times 550.$

As already stated, the relation found between the frequency distribution of deadweight tonnage categories and the average deadweight tonnage must be regarded as a rough generalisation. Because of this, an investigation was made in a number of cases to see how a given calculated figure would be affected if a distribution were applied which was different from the standard frequency distribution. Furthermore, the effect of subdividing the vessel mix into more deadweight tonnage categories, namely 12 instead of 8, was investigated in a limited number of instances. The alternative frequency distributions of standard vessels applied are summarised in Appendix I.

3.3 Deadweight tonnage and vessel utilisation

The utilisation of the carrying capacity of a vessel or a number of vessels refers to:

- the deadweight tonnage utilisation of the individual laden vessel,
- the vessel utilisation of a number of vessels.

In the first case the deadweight tonnage utilisation of a laden vessel is equal to the ratio of the tonnage carried to the deadweight tonnage of the vessel. According to investigations carried out by the Netherlands Institute of Transport this ratio, averaged over a long period, is equal to 0.85. Although variations may occur in practice, for example when low river water-levels make draught limitation necessary, the value 0.85 has been used in further calculations.

The vessel utilisation is defined as the proportion of the number of laden vessels (symbol λ) to the total number of vessels. At many points on the Netherlands waterway network there are considerable differences in deadweight tonnage utilisation according to the direction of navigation. This is due to the unbalanced nature of bulk goods traffic, which means that there is usually no return cargo available for a vessel's return journey. $\lambda = 0.6$ may be taken as a rough average value for traffic in both directions added together.



Photo 2. Example of an old lock (at Hansweert, location Figure 5, No. 14).

4. The entry and exit times of vessels as a component of the locking cycle

4.1 Type and dimensions of lock

Modern locks are designed so as to enable the locking process to proceed as efficiently as possible. The lock chamber and lock approaches are constructed and equipped in such a manner as to avoid the necessity for complicated and time-consuming manoeuvres on the part of vessels entering or leaving. As regards the shape, this means among other things compliance with the following requirements:

- the lock chamber must have a rectangular cross-section (vertical walls)
- the chamber must have a constant width, equal to the navigable width at the lock gates ($B = B_k$)
- the lock approaches must be in line with the lock chamber
- the lock approaches must be provided with properly located lay-bys and guide jetties
- in the case of locks with parallel chambers, the chambers must be so located that vessels entering or leaving do not interfere with one another.

In the case of old locks the width of the chamber is often greater than the width at the gates, while in many cases the lock basins may be said to be inconvenient and unsuitably equipped.

Photographs 1 and 2 show a modern lock and an old lock respectively.

When determining the entry and exit times of vessels, the main emphasis will be placed on locks with a modern shape. The important dimensions in this connection are given in Figure 4.

4.2 Investigation into the entry and exit times of the individual vessels

An investigation was carried out into the following times:

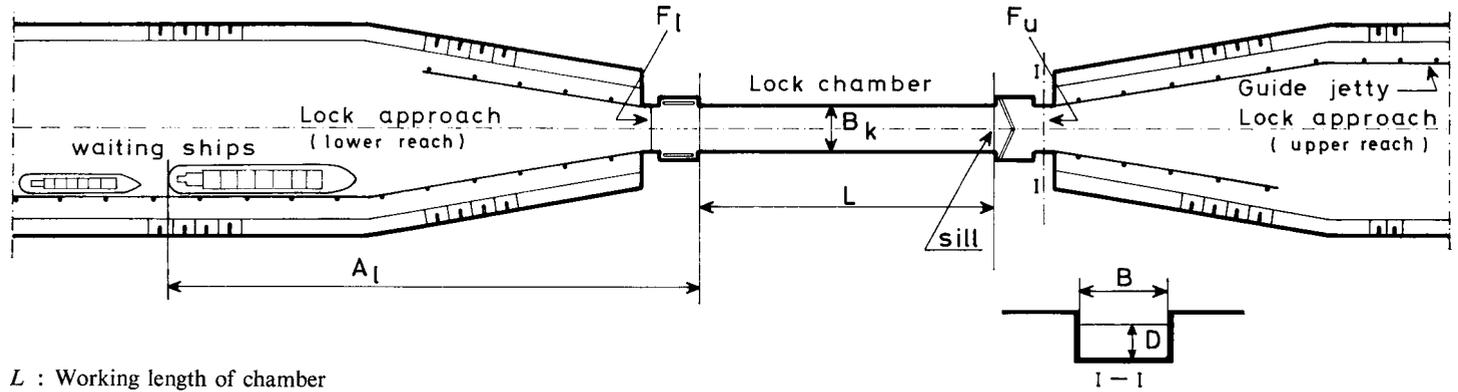
t_i : entry interval

t_u : exit interval

t_l : switch interval

The intervals referred to are defined in Figure 1 (Section 2.1).

To obtain sufficient information for the determination of entry and exit intervals, observations were made at 21 locks with a total of 30 chambers. These were carefully selected to ensure sufficient variety as regards the type of waterway, types of vessel



- L : Working length of chamber
- B : Width of lock entrance
- B_k : Working width of chamber
- F : Area of wet cross-section above sill or lock floor at the lock gate ($B \times D$)
- A_l : Switch distance (from first ship to enter - to gates)

$$F_l = B \times D_l$$

$$F_u = B \times D_u$$

Figure 4. Relevant lock dimensions.

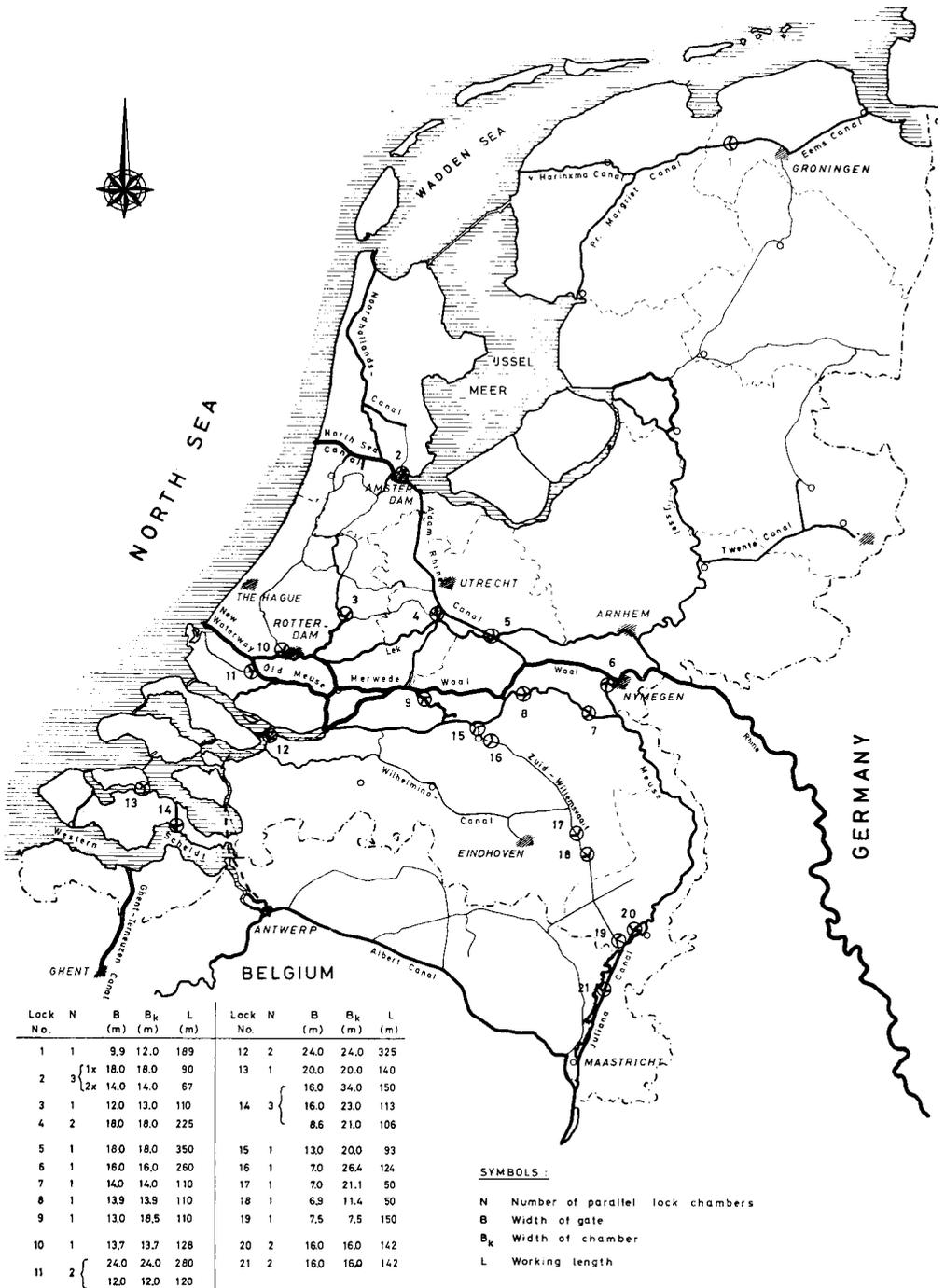


Figure 5. Location of locks where entry and exit times have been measured.

and the shape and dimensions of the locks. The locks selected, which are situated in different parts of the country, are shown in Figure 5, which also gives details of the principal dimensions of the lock chambers.

First of all an examination was made per lock chamber and per type of vessel of the relation between entry and exit times on the one hand and the deadweight tonnage of the vessels on the other, a distinction being made between laden and unladen vessels and between motor vessels (including push-tows) and towed barges.

Generally speaking, the measurement results display a considerable spread, which is to a large extent attributable to the human element. A possible second reason is the difference in the manoeuvrability of vessels. Some examples of measurement results are given in Figure 6.

Using the least squares method, the most suitable polynomials of the first or second degree have been determined for the groups of scattered points. These polynomials have been used as a basis for determining t_i and t_u as a function of the deadweight tonnage of the vessels.

However, it was only possible to determine polynomials satisfactorily for the motor vessels, because the number of observations relating to the towed barges was too small. What has become clear is that it takes longer to manoeuvre towed barges than motor vessels, a fact which has an adverse effect on the entry and exit times.

From the results of the observations it was possible to draw the following conclusions with regard to entry and exit times:

- a. Entry and exit times lengthen as the deadweight tonnage of the vessels increases; this much is obvious.
- b. The entry and exit times of unladen vessels are significantly shorter than those of laden vessels. A distinction has therefore always been made between laden and unladen vessels in the further processing of the results.
- c. There is a marked increase in the length of the entry and exit intervals of a vessel with a given deadweight tonnage as the area of the wet cross-section (F) at the lock entrance decreases. Firstly, an important role is played in this by the vessel's resistance, which increases as the depth of water and the navigable width decrease. Secondly, relatively wide locks enable vessels to enter or leave the chamber side by side or diagonally one after the other, which results in a substantial reduction in entry and exit intervals. An example of the effect of F on t_i and t_u is given in Figure 7.
- d. Conclusions a., b. and c. also apply to the switch time. The switch time also depends on the switch distance (A_D).
- e. In every case the switch time was longer than the entry interval.

4.3 Entry and exit times of standard vessels

The results of the observations show that the entry and exit times of a given vessel are

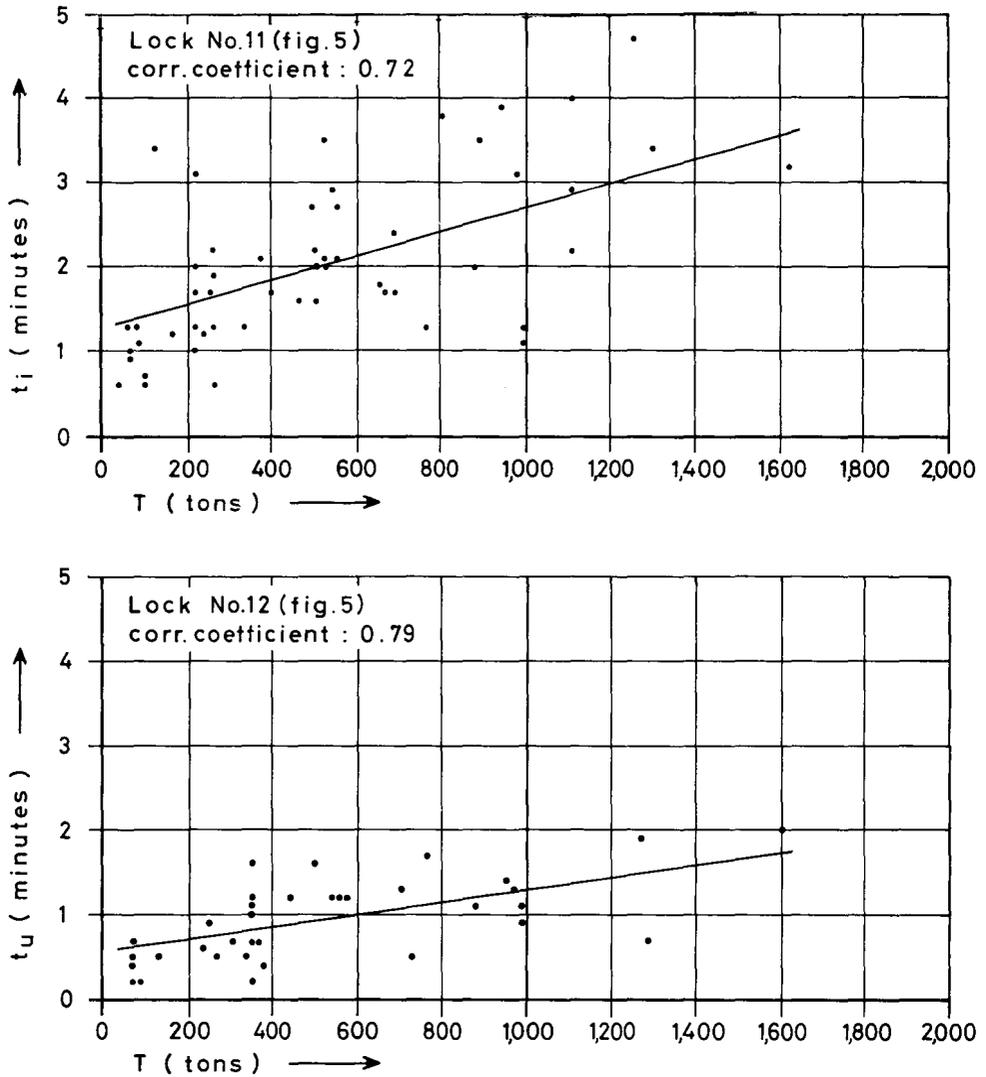
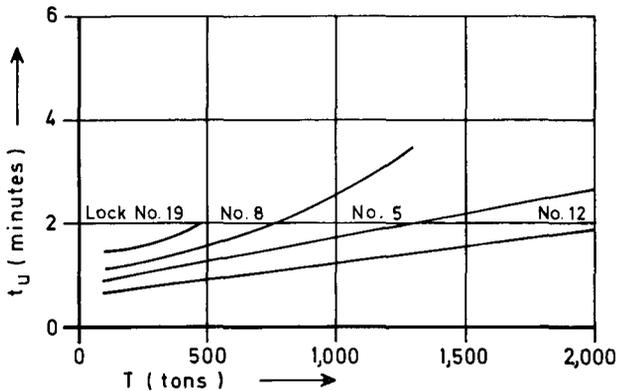
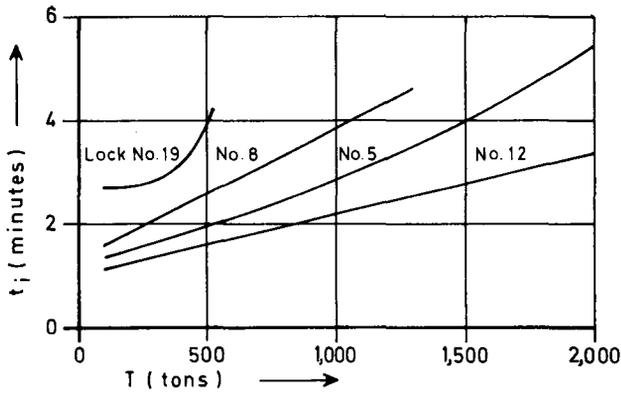


Figure 6. Typical measurement results relating to laden self-propelled vessels.

related to the area (F) of the wet cross-section at the lock entrance. To show the effect of F the non-dimensional quantity f/F is introduced, where f is the area of the largest wet cross-section of the vessel during passage through the lock. f/F indicates what part of the lock entrance or exit is taken up by the vessel. It can thus be stated generally that t_i and t_u are a function of f/F .

Using the results of the observations a general relation between t_i and t_u on the one hand and f/F on the other has been derived for all standard vessels. An example is



Lock No. (fig. 5)	Lock gate		
	B(m)	D(m)	F(sq.m)
12	24.0	6.4	154
5	18.0	5.4	97
8	14.0	3.5	49
19	7.5	2.5	19

Figure 7. Effect of the dimensions of the wet cross-section of the gates on entry and exit times (laden motorvessels).

given in Figure 8 of such a relation for the entry interval of laden standard vessels. A complete picture will be found in Appendix II.

The following should be noted with regard to the graphs of the functions of the entry and exit times of standard vessels.

- The graphs only apply to self-propelled standard vessels.
- The graphs are only applicable to locks having a modern shape as defined in Section 4.1.
- Two principles have been observed in compiling the graphs. Firstly, each line had to link up as closely as possible with the results of the observations. Secondly, the lines had together to form a logical pattern; a number of adjustments were made to achieve this.

The switch time is dependent on the switch distance (A_1) as well as on f/F . The problem arises when determining the switch time that the latter is in fact made up of two parts.

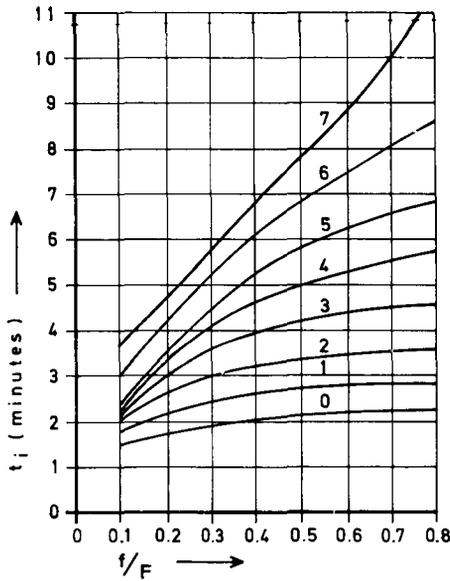


Figure 8. The entry interval (t_i) of laden standard vessels as a function of f/F .

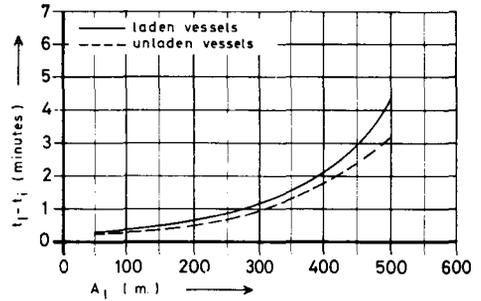


Figure 9. Correction graph for the switch interval.

The first part relates to the time in which the last vessel from the preceding lockage covers the distance A_l , while the second part is the entry time of the first vessel of the lockage being observed (see also Section 2.1). Generally speaking, however, the last-mentioned time constitutes far and away the larger part of the total switch time. This means that an error in the first part only has a limited effect on the total switch time. In view of this consideration and for the sake of simplicity the switch time of a standard vessel is taken as being only a function of f/F and A_l and therefore independent of the size and deadweight tonnage utilisation of the last vessel leaving the lock. The following approximation has been chosen for determining the switch time of a standard vessel:

$$t_l = t_i + \text{correction} \quad (9)$$

The correction is a function of A_l . Using the switch times observed, a relation has been derived for the size of the correction and A_l , and this is given in graph form in Figure 9.

4.4 Relation between entry and exit times and the average deadweight tonnage of the vessels concerned

During investigation of the vessel mix on inland waterways in the Netherlands there

was found to be a fairly close relation between the average deadweight tonnage and the frequency distribution of the deadweight tonnage categories (see Section 3.2). This fact was used to determine the average entry and exit time per vessel as a function of the average deadweight tonnage (\bar{T}) and the area of the wet cross-section at the lock gate (F). For this purpose the vessels in a given deadweight tonnage category are represented by a standard vessel whose characteristics are given in Table 3.2.1.

The following basic assumptions have also been made.

- The relation found between the frequency distribution of the deadweight tonnage categories and \bar{T} is valid generally; the effect of deviating distributions is gone into in more detail later in this section.
- The frequency distribution of the deadweight tonnage categories for a given value of \bar{T} is considered as a probability distribution for the proportion of the various standard vessels in the total number of vessels to be passed through the lock. In other words the probability that any vessel arriving belongs to class s is equated to probability p_s of it being standard vessel s .

The average values of t_i and t_u can be calculated as follows for selected values of F and \bar{T} :

$$\bar{t}_i = \sum_{s=1}^m \{p_s t_{is}\} \quad (10)$$

and

$$\bar{t}_u = \sum_{s=1}^m \{p_s t_{us}\} \quad (11)$$

where m is the highest deadweight tonnage category of the frequency distribution applied which is appropriate to the selected value of \bar{T} . Further, t_{is} and t_{us} are the entry and exit intervals of the standard vessels as a function of f/F .

In the first instance determination of \bar{t}_i and \bar{t}_u has been based on the standard frequency distributions which are given in Table 2 of Appendix I for a large number of values of \bar{T} . An example of the results of this approximation are given in Figure 10. A complete summary will be found in Appendix II (Figures 2 to 5).

The correction graph in Figure 9 should be used when determining the average switch time \bar{t}_1 (see also Appendix II).

The average values of t_i , t_u and t_l which have been determined in the manner just described will be further applied in the calculation of the lock capacity and the transit time of vessels. It is therefore important to examine to what extent these entry and exit times depend on the vessel mix, in this case the frequency distribution of the deadweight tonnage categories. For this purpose a number of calculations have been carried out on a random basis, whereby \bar{t}_i and \bar{t}_u have been determined for various values of

F and \bar{T} , but various frequency distributions of standard vessels have been used for a single value of \bar{T} , the standard deviation (S) being used as a parameter. The standard deviations are summarised in Table 3 of Appendix I.

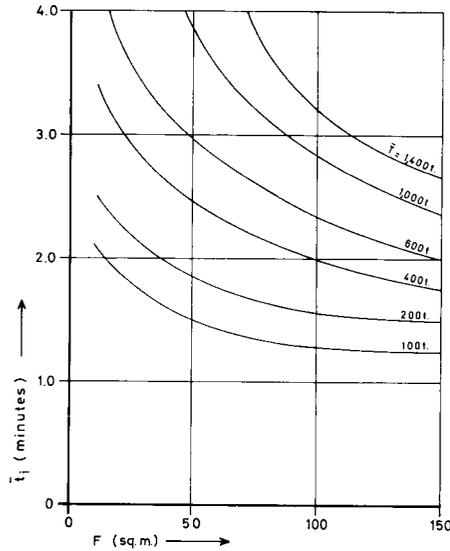


Figure 10. The relation between the average entry interval (\bar{t}_i) of laden self-propelled vessels and the area of the wet cross-section (F) at the lockage for various average tonnages.

The calculations have been carried out for small, medium-sized and large locks. The results, some of which are given in Figure 11, show that the effect of the distribution of standard vessels is, generally speaking, slight. Only in the case of distributions with relatively speaking very large standard deviations, in other words where the vessel mix is exceptional, can there be said to be a small effect on t_i . The likelihood of such vessel mixes occurring in practice is, however, slight because the small vessels are being increasingly replaced by larger ones, with the result that the standard deviation of the distribution is being reduced.

It can be concluded on the basis of what has gone before that the empirically determined relations between \bar{t}_i and \bar{t}_u on the one hand and \bar{T} and F on the other are generally applicable to locks situated on waterways in the Netherlands. Any deviations will amount to no more than a few per cent.

The average values of the entry and exit intervals are valid for locks with a modern shape (Section 4.1). If the shape of the lock chambers differs significantly from this, e.g. $B_k \gg B$, higher values should be allowed for. Because, however, of the wide variation in the shapes of the chambers of old locks, it is not possible to give exact correc-

tion factors. It is recommended that these be ascertained by means of observations on the spot.

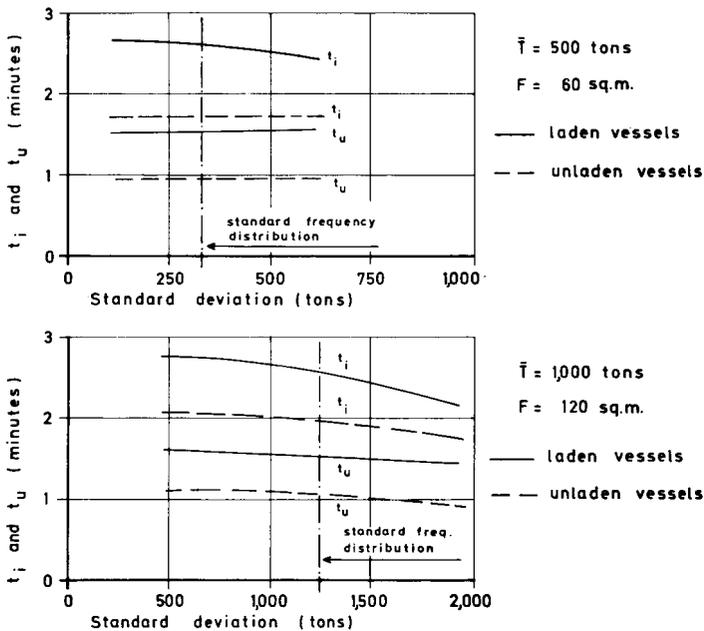


Figure 11. Effect of the vessel mix on the entry and exit intervals.

It is, nevertheless, possible to give some indication on the basis of observations already made. The following correction factors should be used, broadly speaking, for locks Nos. 14 to 18 in Figure 5:

laden vessels (for \bar{t}_i and \bar{t}_u): 1.10 to 1.15

unladen vessels (for \bar{t}_i and \bar{t}_u): 1.20 to 1.30

A correction should be applied to the switch time if the following circumstances obtain:

- the lay-by occupied by the first vessel is unfavourably situated in relation to the lock entrance.
- where a lock has more than one chamber, vessels entering one chamber are hindered by those leaving the other.

In both cases the correction factor should be estimated on the basis of a study of the situation.

5. Operating time as a component of the locking process

The operating time, T_b , begins at the moment when entry of the last vessel has been completed and ends at the moment when the doors on the exit side have been opened. T_b is made up of two components, viz. the movement of the gates and the filling or emptying of the chamber.

In the case of the majority of locks it takes longer to close the gates than to open them. The reason for this is that the lock operator supervises the entry into the lock and the mooring of the vessels. When the last vessel has entered he has to make sure that the vessels are clear of the gate(s), this being particularly important if the chamber is full of vessels. He then goes to the control room to close the gate(s). The delay involved does not generally exceed 0.5 to 1.0 minutes.

The results of a number of observations made under working conditions are shown in Table 5.1 in order to give an idea of the time required on average to close and open the gates. These show that vertical lift gates require more time to operate than other types of gate.

In the case of the most modern locks aids such as T.V. cameras are employed. The lock operator can then supervise entry from the control room, with a resulting reduction in the gross closing time (e.g. at lock No. 20).

Lock (see Figure 5)	Type of gate	Closing (min.)	Opening (min.)
3	rolling gates	1.2	0.7
4	vertical lift gates	3.0	2.1
8	vertical lift gates	3.3	2.3
11	mitre gates	2.5	1.6
20	mitre gates	1.3	1.2
21	mitre gates	2.1	1.3

Table 5.1 Gross times for the opening and closing of lock gates (all locks are electrically operated).

The filling and emptying of the chamber is dependent on a large number of factors including the lift, the length and width of the chamber and the filling and emptying system.

In the case of far and away the greater proportion of locks in the Netherlands filling

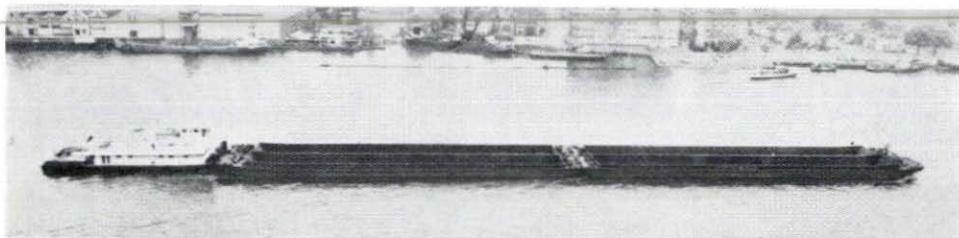
and emptying takes place via the ends of the locks e.g. through vertical lift valves or short culverts, or by raising the vertical lift gates, if these are present. Because the lift is in general relatively small, acceptable filling and emptying times can be achieved by these systems. One way of helping to make sure that this is so is to have the filling and emptying system of a new lock tested in advance at the Hydraulics Laboratory in Delft, which has considerable experience in this field. The criterion used in the tests carried out there relates to the amount of pull on the hawsers with which vessels are moored.

To give an idea of filling and emptying times a number of average values, based on observations under working conditions, are shown in Table 5.2.

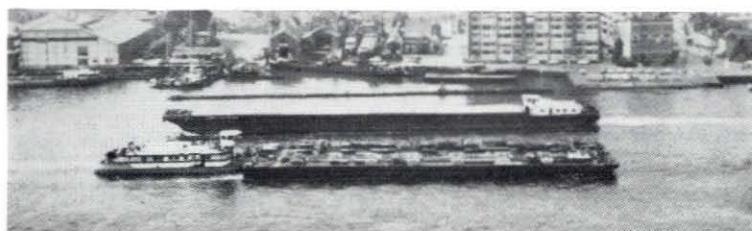
Lock (see Figure 5)	Construction completed	L (m)	B (m)	H (m)	Filling (min.)	Emptying (min.)
21	1962	142	16	11.0	10.8	9.7
20	1970	142	16	6.6	6.7	7.5
8	1936	110	14	4.4	8.2	9.4
11	1968	280	24	<0.5	4.5	5.0
				0.5-1.7	±6.0	±7.5
4	1938	225	18	<0.5	5.3	5.3
				0.5-1.4	±7.0	±8.1

Table 5.2 Filling and emptying times of a number of locks.

In the case of locks with special systems, as where economising basins are used for example, filling and emptying times may be appreciably longer. Shorter times can be achieved by using a system of longitudinal culverts with branches, so that the chamber can be filled or emptied simultaneously over its whole length and the pull exerted on the hawsers is kept to a minimum. The Belgian lock at Ternaaien between the Meuse and the Albert Canal (16 × 136 sq.m.) is equipped with such a system. A lift of approximately 16 m is achieved here in 12 to 13 minutes.



Category 7 (ca 9000 tons),



Category 6 (ca 4500 tons),

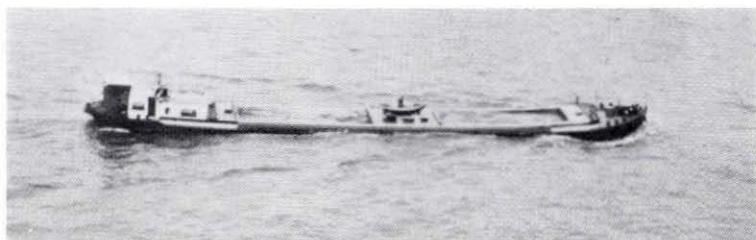


Category 4 (ca 1350 tons),

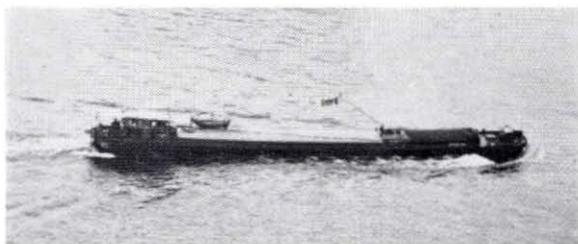
Photo 3. Ships of various tonnage categories.



Category 4 (ca 1350 tons),



Category 2 (ca 550 tons),



Category 1 (ca 325 tons).

Photo 3. Ships of various tonnage categories.

6. The maximum number of vessels in the lock chamber

6.1 In-chamber vessel arrangement simulations and observations under working conditions

An important factor in the calculation of lock capacity is the maximum number of vessels (n_{\max}) that a chamber can hold. During a series of consecutive lockages with full chambers n_{\max} will generally vary from one lockage to another. It is, however, sufficient to know the average value of n_{\max} as a function of the average deadweight tonnage \bar{T} of the vessels that pass through the lock during a given period.

In-chamber vessel arrangement simulations have been carried out to enable n_{\max} to be determined for a large number of chamber sizes. As in the determination of the average entry and exit times, it has been assumed that the vessel mix consisted of standard vessels whose frequency distribution is a function of \bar{T} (see Section 3.2). The simulations were first of all performed by hand on paper, the lock chambers and standard vessels being reproduced to scale. Since the vessels were represented by rectangles, the area occupied by each vessel was somewhat greater than that occupied in reality.

Subsequently use has been made of a computer program which, completed in 1974, was developed by the Data Processing Department in collaboration with the Traffic Engineering Department (both departments of 'Rijkswaterstaat').

The first-mentioned simulation (by hand) proceeds as follows:

1. Select lock chamber dimensions L and B .
2. Ascertain the navigability class (largest standard vessel to be admitted).
3. Select the average deadweight tonnage \bar{T} .
4. Determine the proportion of each standard vessel in the vessel mix by applying the standard frequency distribution as a function of \bar{T} . The simplest way of doing this is to use Table 2 of Appendix I, taking for \bar{T} one of the values appearing in it. Account has to be taken of the navigability class when choosing the frequency distribution.
5. Prepare a long queue of vessels, drawing random numbers to determine the order of arrival of the standard vessels (a table of random numbers is used). The probability of a given standard vessel coming up is then equal to the proportion of such vessels in the vessel mix as determined in 4.
6. Fill the chamber, which has been reproduced to scale, with standard vessels, applying rules derived from actual experience. This involves the following:
 - Aiming to achieve the maximum number of vessels per lockage (space between vessels in the lengthwise direction about 3% of a vessel's length, and in

the crosswise direction in total at least 1% to 2% of the width of the chamber).

- A vessel whose turn is next on the basis of the order of arrival cannot be passed over.
 - If the chamber contains $n - 1$ vessels and the space remaining is too small for the n th vessel, the subsequent vessel is, if possible, taken from the queue, and so on. Generally it is not usual to look beyond the $(n + 3)$ th vessel when following this procedure.
7. Note the number of vessels in the chamber and calculate \bar{T} .
 8. Repeat 6 and 7 with subsequent vessels from the queue (a total of approximately 20 lockages are carried out by hand).
 9. Determine n_{\max} as the average number of vessels per 'full' lockage together with the corresponding value of \bar{T} (because the vessels have been drawn at random the \bar{T} obtained by calculation may differ to some extent from the \bar{T} selected).
 10. Repeat 3-9 for a newly selected value of \bar{T} . Generally between 3 and 5 values of \bar{T} are used, depending on the size of the chamber.

Virtually the same method is applied with computer simulation as with simulation by hand. Only in the placing of the vessels in the chamber can there be said to be any difference in method. In the case of simulation by hand it is easy to judge what is the best arrangement in the chamber. In the case of the computer simulation an attempt is always made to find a place for the next ship in the queue. This order is departed from if the second, third or fourth vessel can be placed further forward; at the same time, however, the principle stated in 6 is applied that a vessel cannot be passed over if it comes next on the basis of the order of arrival.

Carrying out simulations by hand is a time-consuming and monotonous business. For this reason the number of lockages is kept as small as possible, especially where chambers are large. The same disadvantage does not of course apply to computer simulation.

In Figure 12 a comparison is made for a large, a medium-sized and a small lock between the results of the two methods, and between these and observations made under working conditions. In view of the considerable measure of agreement the conclusion can be drawn that it has been shown experimentally that the two methods of simulation used yield reliable results for the determination of n_{\max} as the average value from a large number of lockages.

6.2 The effect of the vessel mix on the maximum number of vessels in the chamber

The fact that the standard frequency distribution of standard vessels has been used as a function of the average deadweight tonnage means that a vessel mix is being worked with which has been schematised as follows:

- the mix has been built up of a maximum of 8 different standard vessels.

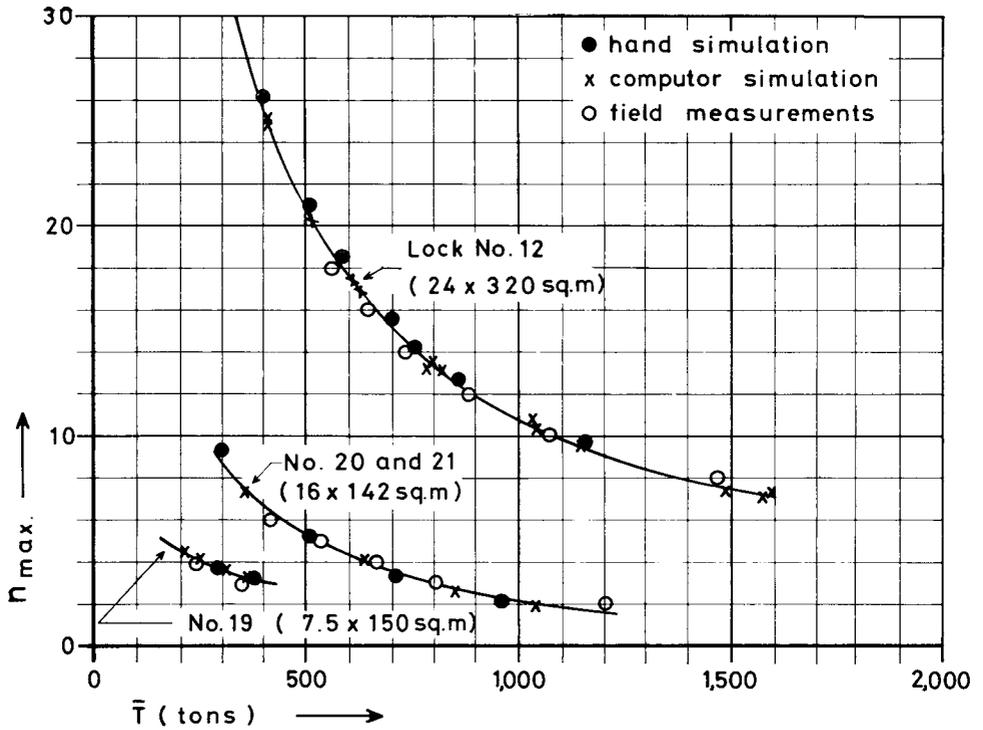


Figure 12. Maximum number of vessels the lock chamber can hold (n_{max}) in relation to the average tonnage (\bar{T}).

- the proportion represented by each standard vessel is constant for a given value of \bar{T} .

To examine the effect of these schematisations on n_{max} a supplementary investigation was instituted using the computer simulation. The following vessel mix variants were employed.

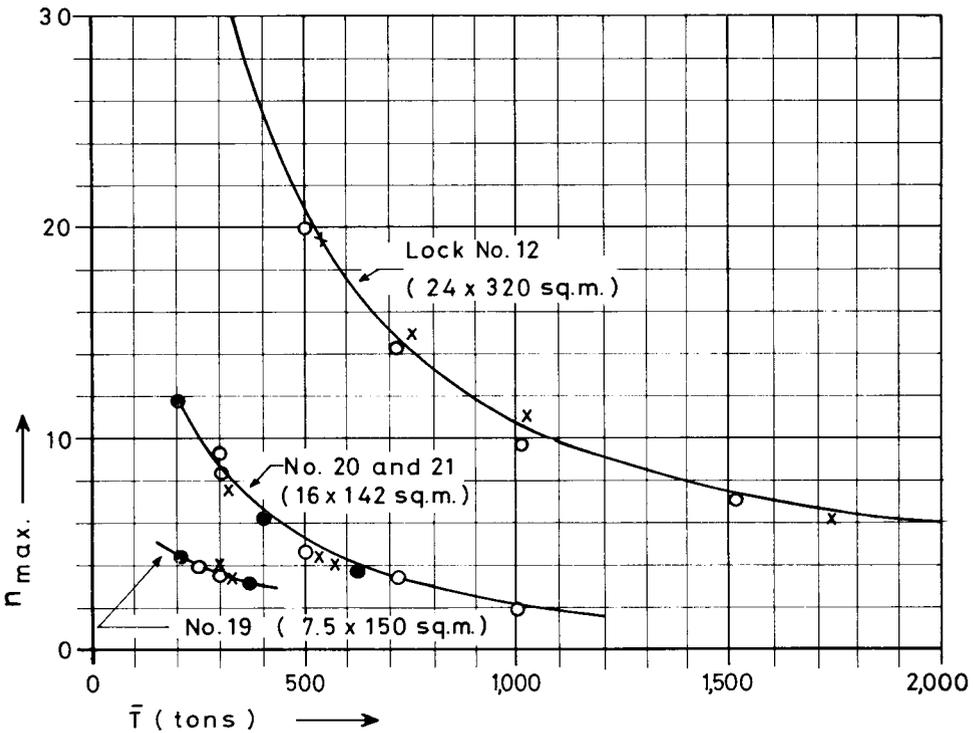
- a. Subdivision in terms of 12 standard vessels (instead of 8), assuming the vessel mix shown in Figure 1 of Appendix I. The deadweight tonnage categories 1, 2, and 3 have been subdivided respectively into 2, 3 and 2 categories. The wider variety of sizes enables the chamber, particularly in the case of small locks, to be more fully utilised. Details of these 12 standard vessels and the frequency distributions as a function of \bar{T} are given in Table 4 of Appendix I.
- b. Subdivision in terms of the usual 8 standard vessels, but with deviating frequency distributions. The distributions used have a standard deviation S which may be either larger or smaller than the standard deviation of the standard frequency distribution. The deviating distributions will be found in Table 3 of Appendix I.

The effect of differing vessel mixes on n_{max} is shown in Figure 13 for several different sizes of lock.

Subdivision into 12 categories, which has only been applied to the medium-sized and small lock chambers, gives the same result as division into 8 categories.

A vessel mix obtained in the manner described in b. results in a number of small deviations, the effect of which on lock capacity can in general be disregarded.

It can be concluded from the results of this supplementary investigation that the use of a schematised vessel mix built up from 8 different standard vessels in accordance with the standard frequency distribution (Table 2, Appendix I) gives reliable results in the determination of the maximum number of vessels that a given lock chamber can hold on average.



8 deadweight tonnage categories

- standard frequency distribution
- × distribution with large standard deviation
- distribution with small standard deviation

12 deadweight tonnage categories

- distribution based on data relating to the international vessel mix on the Rhine.

Figure 13. Effect of the vessel mix on the maximum number of vessels the lock chamber can hold.

6.3 The maximum number of vessels in the lock as a function of the average deadweight tonnage

Using the simulation method described in Section 6.1, n_{\max} has been determined as a function of \bar{T} for a large number of lock chamber sizes, chamber length and width being systematically varied. The smallest chamber measure 7×50 sq.m., the minimum dimensions of a lock in navigability class 2. The largest lock measures 24×400 sq.m., this being a lock in navigability class 8 where there is room for two large push-tows one behind the other.

A complete summary of the results is given in the form of graphs in Appendix III. These results will be used further as a basis for the calculation of lock capacities.

7. Computation of lock capacity

7.1 Method of computation

As stated in Section 2.2 three cases can be distinguished with regard to lock capacity. These are:

- a. lockages with full chambers in both directions.
- b. lockages with full chamber in one direction and partly full chamber in the other direction.
- c. lockages with full chamber where traffic is in one direction.

Case a. will first be dealt with for the purpose of explaining the method of computation.

Lock capacity C_s is first determined as a function of the average deadweight tonnage \bar{T} by calculating C_s for several values of \bar{T} using equation (5) in Section 2.2. The points of the calculated coordinates (C_s , \bar{T}) are plotted on a graph and then joined together by a curved line. C_s can then be read off as a function of \bar{T} .

For a selected value of \bar{T} a calculation sequence can be followed such as will now be described step by step. Fuller information is given on a number of points. An inland waterway lock of modern shape is assumed.

A. DATA RELATING TO THE LOCK

1. Ascertain the effective length (L) and width (B) of the lock.
2. Calculate the area of the wet cross-section at the upper gate (F_u) and lower gate (F_l);
 $F_u = B \times D_u$ and $F_l = B \times D_l$. For simplicity, average values may be used in tidal areas.
3. Determine the distance from the lock gate to the start of the lay-by ($\bar{A}_l - \bar{T}$).
4. Determine the operating time T_b for both lockage directions by estimating or measuring the time taken in the case of a similar existing lock (see also Chapter 5).

B. DATA RELATING TO VESSEL MIX

1. Determine the composition of the vessel mix making a broad distinction between the categories, inland waterway vessels (self-propelled and otherwise), other

professional shipping and pleasure craft. Note: the calculation of lock capacity is based on self propelled inland waterway vessels. If towed vessels or the other categories constitute a large proportion of the vessel mix, a reduction will have to be made in the calculated capacity.

2. Select various values of \bar{T} with the appropriate average vessel length l in accordance with Figure 2 of Appendix I.
3. Ascertain the vessel utilisation λ for each direction of navigation. If it is not known, an average of $\lambda = 0.6$ can be used in the conditions obtaining in the Netherlands.

C. ENTRY AND EXIT TIMES OF VESSELS

1. Using the graphs in Appendix 2, determine entry interval \bar{t}_i , for each direction, for laden and unladen vessels, for the selected values of \bar{T} . In the upstream direction $F = F_l$, in the downstream direction $F = F_u$.
The value for each direction of navigation is given by: $t_i = \lambda \times t_i$ (laden vessels) + $(1 - \lambda) \times t_i$ (unladen vessels).
2. Determine the exit interval \bar{t}_u for each direction of navigation etc. in the same way as the entry interval. Upstream, $F = F_u$; downstream, $F = F_l$.
3. Determine the switch time \bar{t}_1 for each direction of navigation etc., using:
 $\bar{t}_1 = \bar{t}_i + \text{correction}$.
The correction can be determined by using the correction graph in Appendix II. Here A_l (switch distance) is equal to the distance referred to in A.3 plus l .

D. MAXIMUM NUMBER OF VESSELS IN THE CHAMBER

n_{\max} can be read off from the graphs in Appendix III for the various values of \bar{T} .

E. LOCKING TIME IN EACH DIRECTION

The following equation is derived for the locking time from equations (2), (3) and (4).

$$\bar{T}_d = \bar{t}_l + (n_{\max} - 1) \bar{t}_i + n_{\max} \cdot t_u + T_b$$

F. LOCKING CYCLE TIME

The locking cycle time as an average of a large number of lockages is given by

$$\bar{T}_c = \bar{T}_d (\text{upstream}) + \bar{T}_d (\text{downstream}).$$

G. LOCK CAPACITY ON AN HOURLY BASIS

$$C_s = \frac{2n_{\max}}{T_c} \times 60 \text{ (vessels per hour)}$$

$$C_T = \bar{T} \times C_s \text{ (deadweight tons per hour).}$$

As already mentioned in B.1. the actual lock capacity will in many cases be somewhat lower than the calculated capacity. The reduction to be applied must in fact be looked at in each case individually. For conditions obtaining in the Netherlands a reduction of 10% is generally sufficient, provided pleasure cruising is not on a large scale. In some cases this reduction is even somewhat on the high side.

A second reduction should be applied for the hours when the lock is operating in the dark. A reduction of 5% will generally be sufficient for a well-lit lock.

Lock capacity on a weekly basis (C_w) can be simply determined by multiplying C_s or C_T by the total number of hours the lock operates per week, taking into account of course the reduction percentages already referred to.

The whole process of calculation is illustrated in detail by means of an example in Appendix IV.

It is only necessary to make one or two changes in the process of calculation just outlined in order to calculate the capacities referred to in b. and c.

The following changes are of importance in the case of b.

- D: n_{\max} holds good for the direction of navigation for which the capacity has to be determined, in the opposite direction a (measured or estimated) value for $n < n_{\max}$.
- E: For the first-mentioned direction \bar{T}_d is determined on the basis of n_{\max} (equation 12) and for the opposite direction on the basis of n .
- G: The capacity is determined by using equation (7).

The changes relating to c. are as follows:

General: All data relating to the vessel mix, navigation times etc. need only be determined for one direction.

C.3: The switch time has to be replaced by the, shorter, entry time of the first vessel.

F: $\bar{T}_c = \bar{T}_d$ (locking direction) + T_b (opposite direction)

G: Apply equation (7).

7.2 Comparison of measured and calculated capacities

In the case of the 21 locks shown in Figure 5 an investigation was made into the lock-

ing time as well as the entry and exit times of the individual vessels. It was therefore possible to determine the capacity of a number of locks by determining the duration of lockages with full chambers, the number of vessels and the average deadweight tonnage.

The measured capacities are compared in Figure 14 with the calculated capacities of these locks. Several of them have an obsolete shape. The rough corrections in 4.4 have therefore been applied to the entry and exit times. Furthermore, a reduction of 10% has been applied to all the calculated capacities (see 7.1).

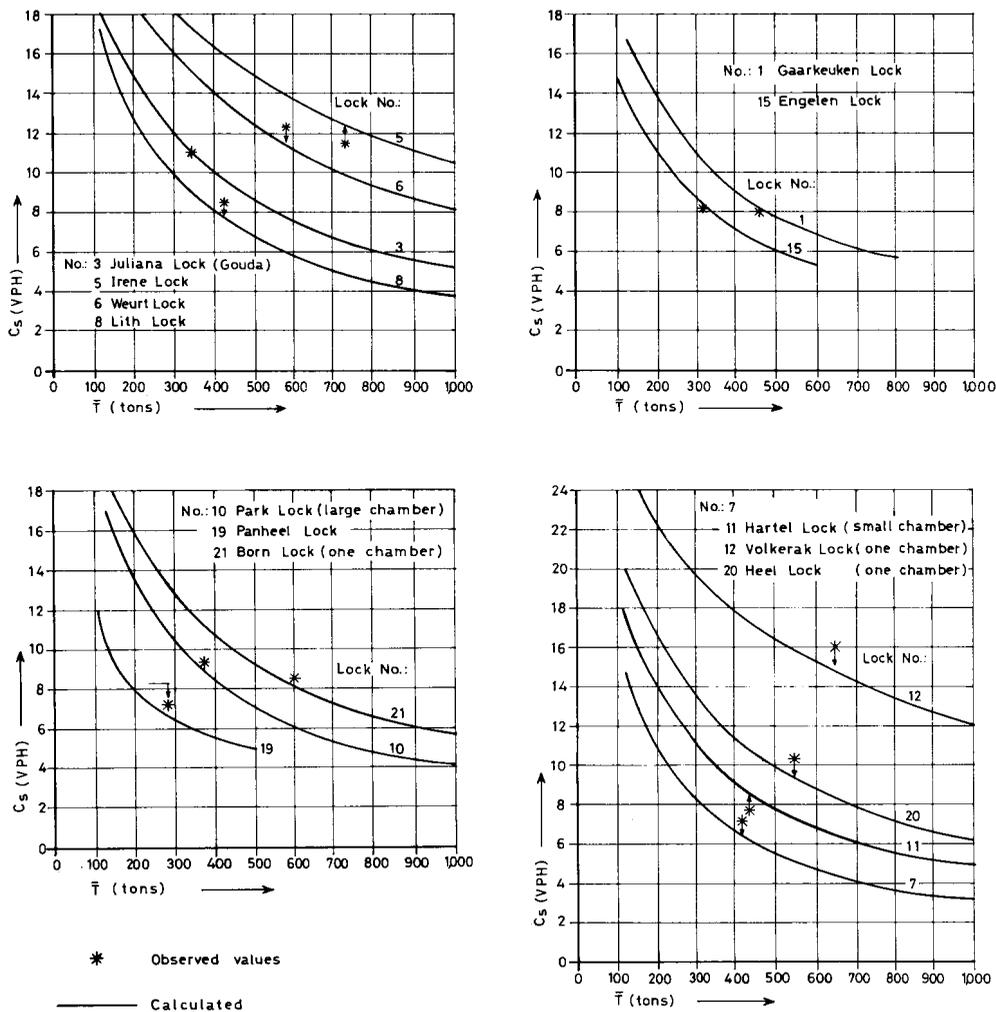


Figure 14. Comparison of lock capacities based on calculations and field measurements (for location of locks and chamber dimensions see figure 5).

The extent to which calculated and measured values coincide may be regarded as satisfactory. Some deviations may be attributable to the relatively small number of lockages with full chambers that have been observed in the case of several locks.

8. Waiting and locking times as components of the transit time

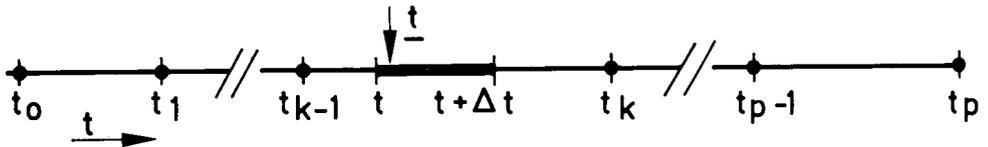
8.1 The average waiting time at a one-chamber lock

Waiting time as a component of transit time has been defined in Section 2.3. The waiting time begins with the theoretical arrival time and ends at the moment when the operating time of the next lockage in the direction of navigation of the vessel being observed begins.

The following assumptions are made for the determination of average waiting time \bar{t}_w of any vessel:

1. The vessel may arrive at the lock at any time t ; in other words the stochastic variable t has a uniform probability distribution.
2. The successive locking cycle times are variable.

A period of p locking cycles, running from t_o to t_p , is considered. Locking cycle k runs from t_{k-1} to t_k , so that $T_k = t_k - t_{k-1}$ and $\sum_{k=1}^p T_k = t_p - t_o = p\bar{T}_c$



The vessel arrives at a point in time t between t_o and t_p . The following equation holds good in the case of a uniform arrival distribution:

$$Pr \left\{ t \leq \underline{t} < t + \Delta t \right\} = \frac{1}{p\bar{T}_c} dt \quad (13)$$

(Δt is very small)

The end of the waiting time is given by the points in time $t_o, t_1 \dots t_k$ for each locking cycle.

The waiting time in locking cycle No. k is:

$$t_w = t_k - t \quad (14)$$

The average waiting time for the period under consideration is:

$$\begin{aligned}
 \bar{i}_w &= \frac{1}{p\bar{T}_c} \left[\int_{t_0}^{t_1} (t_1 - t)dt + \dots + \int_{t_{k-1}}^{t_k} (t_k - t)dt + \dots + \int_{t_{p-1}}^{t_p} (t_p - t)dt \right] \\
 &= \frac{1}{p\bar{T}_c} \left[\frac{1}{2}(t_1 - t_0)^2 + \dots + \frac{1}{2}(t_k - t_{k-1})^2 + \dots + \frac{1}{2}(t_p - t_{p-1})^2 \right] \\
 &= \frac{1}{p\bar{T}_c} \left[\frac{1}{2}T_1^2 + \dots + \frac{1}{2}T_k^2 + \dots + \frac{1}{2}T_p^2 \right] \\
 \bar{i}_w &= \frac{1}{2p\bar{T}_c} \sum_{k=1}^p T_k^2 \tag{15}
 \end{aligned}$$

T_k may be written as follows:

$$T_k = \bar{T}_c + \Delta T_k \quad (k = 1, \dots, p)$$

Substitution in equation (15) then gives

$$\begin{aligned}
 \bar{i}_w &= \frac{1}{2p\bar{T}_c} \sum_{k=1}^p \{\bar{T}_c + \Delta T_k\}^2 \\
 &= \frac{1}{2p\bar{T}_c} \sum_{k=1}^p \{\bar{T}_c^2 + 2\bar{T}_c\Delta T_k + (\Delta T_k)^2\} \\
 &= \frac{1}{2p\bar{T}_c} \cdot \left[p\bar{T}_c^2 + 0 + \sum_{k=1}^p (T_k - \bar{T}_c)^2 \right] \\
 \bar{i}_w &= \frac{1}{2}\bar{T}_c + \frac{\text{Var}(T_c)}{2\bar{T}_c} \tag{16}
 \end{aligned}$$

Generally speaking, the second term on the right-hand side of the equation only contributes a very small amount to the average waiting time. Even in the case of very large variations in cycle times, which can only occur with very large lock chambers where the number of vessels arriving is so irregular that lockages with a full chamber are interspersed with lockages involving only a single vessel, the contribution of the term in question is not more than a few per cent. For calculation of the waiting time it is therefore sufficient to use the equation:

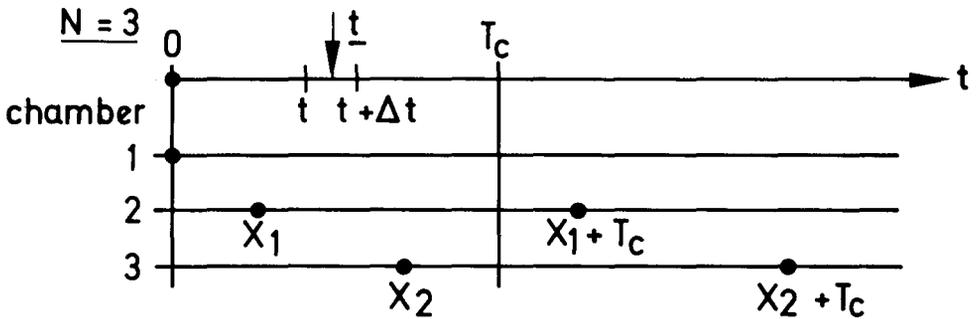
$$\bar{i}_w = \frac{1}{2}\bar{T}_c \tag{17}$$

8.2 The average waiting time at a lock with N parallel chambers

The following assumptions are made for the determination of the average waiting time of any vessel arriving at a lock with N chambers ($N = 1, 2, 3 \dots$):

1. The vessel may arrive at the lock at any time t , in other words t has a uniform probability distribution.
2. For every lock chamber the locking cycle time T_c is constant and equal to the average value relating to a given volume of vessels arriving and a given vessel mix.
3. If $N \geq 2$, the locking cycle times of the various chambers are equal to one another. This will be the case if the chambers are identical as regards shape, size and operating time.
4. If $N \geq 2$, it is assumed that the phase differences between the locking cycles of the various chambers are of a random nature, a uniform probability distribution being assumed.

On the basis of the assumptions just referred to the waiting time can be derived analytically as a function of N and T_c . To provide an insight into the method employed the waiting time will now be derived, first for a lock with 3 chambers, and then for one with N chambers.



The vessel arrives at a random point in time t between $t = 0$ and $t = T_c$. The arrival time has a uniform distribution:

$$Pr \{t \leq t < t + \Delta t\} = \frac{1}{T_c} dt.$$

The locking cycle of the first chamber runs from 0 to T . The starting times of the locking cycles of the second and third chambers are X_1 and X_2 respectively. The stochastic variables X_1 and X_2 are uniformly distributed over the interval $(0, T_c)$. The probability density functions relating to X_1 and X_2 are in this case:

$$Pr \{X_1 \leq \underline{X}_1 \leq X_1 + \Delta X_1\} = \frac{1}{T_c} dX_1$$

and

$$Pr \{X_2 \leq X_2 \leq X_2 + \Delta X_2\} = \frac{1}{T_c} dX_2$$

Two cases must be distinguished when calculating t_w : $X_2 > X_1$ and $X_2 < X_1$.

Case 1. $X_2 > X_1$

Arrival time t may lie between:

- a. 0 and X_1 $t_w = X_1 - t$
- b. X_1 and X_2 $t_w = X_2 - t$
- c. X_2 and T_c $t_w = T_c - t$

Case 2. $X_2 < X_1$

Case 2 is identical with case 1, except that X_1 and X_2 are reversed. Both cases will therefore give the same result.

$$\begin{aligned} \bar{i}_w &= \frac{2}{T_c^3} \left[\int_0^{T_c} \int_0^{X_2} \left\{ \int_0^{X_1} (X_1 - t) dt \right\} dX_1 dX_2 + \int_0^{T_c} \int_0^{X_2} \left\{ \int_{X_1}^{X_2} (X_2 - t) dt \right\} dX_1 dX_2 + \right. \\ &\quad \left. \int_0^{T_c} \int_0^{X_2} \left\{ \int_{X_2}^{T_c} (T_c - t) dt \right\} dX_1 dX_2 \right] = \\ \bar{i}_w &= \frac{2}{T_c^3} \left[\frac{1}{24} T_c^4 + \frac{1}{24} T_c^4 + \frac{1}{24} T_c^4 \right] = \\ \bar{i}_w &= \frac{1}{4} T_c \end{aligned}$$

N chambers

There are $(N - 1)!$ possibilities for the arrangement of the starting times of the locking cycles. As in the case of $N = 3$ each arrangement contributes equally to the value of t_w . The proportion of the waiting time constituted by a particular arrangement consists of a sum with N terms. Each term is an N -fold integral of the following form:

$$\frac{1}{T_c^N} \left[\int_0^{T_c} \int_0^{X_{N-1}} \dots \int_0^{X_2} \int_0^{X_1} \left\{ \int_{X_{k-1}}^{X_k} (X_k - t) dt \right\} dX_1 dX_2 \dots dX_{N-1} \right]$$

Analogously with the case $N = 3$, the average waiting time is:

$$\bar{i}_w = (N - 1)! \frac{1}{T_c^N} \left[\frac{T_c^{N+1}}{(N + 1)!} + \frac{T_c^{N+1}}{(N + 1)!} + \dots + \frac{T_c^{N+1}}{(N + 1)!} \right]$$

$$\bar{i}_w = (N - 1)! \frac{1}{N} \cdot N \cdot \frac{T_c^{N+1}}{(N + 1)!}$$

$$\bar{i}_w = \frac{T_c}{N + 1} \quad (\text{here } T_c = \bar{T}_c) \quad (18)$$

When applying general equation (18) for \bar{i}_w , it must be remembered that assumptions 2, 3 and 4 will not always be fulfilled in practice. The following deviations may occur:

- As regards assumption 2.

In practice the locking cycle varies. However, the effect of this on \bar{i}_w is slight, as already mentioned in the previous section.

- As regards assumption 3.

Assumption 3 is generally not fulfilled if the lock comprises chambers of different dimensions. The biggest deviations arise if the chambers concerned are in different navigability classes. A number of vessels (the largest) are not then able to make use of all the chambers. For such vessels \bar{i}_w is longer than for vessels which can pass through all the chambers.

A large number of different cases can occur in practice. For this reason it may be desirable to apply a correction to the value of \bar{i}_w calculated in accordance with equation (18).

- As regards assumption 4.

Assumption 4 holds good if the locking process is given 'free rein'. In many cases, however, the lock operators will have to coordinate the lockages to some extent, for safety reasons. It may be desirable, for example, in the case of some twin locks not to allow vessels to sail out of both locks in the same direction simultaneously, a consideration which will result in some lengthening of \bar{i}_w .

The accuracy of assumption 4 will generally speaking increase as N becomes larger.

8.3 The average locking time

The locking time begins when entry has been completed and the entry gates can be

closed. The locking time ends when the stern of the vessel concerned passes the exit gates after being locked. The locking time therefore comprises the operating time T_b and part of the total exit time T_u .

In the case of a lockage with one vessel the locking time is given by:

$$t_s = T_b + t_u.$$

If the lockage involves n vessels, the average locking time per vessel is:

$$t_s = T_b + \frac{1}{2}(n + 1)t_u \quad (19)$$

In practice the number of vessels per lockage will vary. If the exit interval of the vessels is equated to t_u , the following equation can be constructed:

$$\bar{t}_s = T_b + \frac{1}{2}t_u + \frac{1}{2}t_u \frac{\sum_{k=1}^z n_k^2}{\sum_{k=1}^z n_k} \quad (20)$$

Here n_k is the number of vessels in the k th lockage and z the total number of lockages in the period under consideration. If \bar{n} is the average number of vessels per lockage, then

$$\sum_{k=1}^z n_k = z\bar{n}$$

$\sum_{k=1}^z n_k^2$ can be written in the following form:

$$\sum_{k=1}^z (n_k^2 - 2n_k\bar{n} + \bar{n}^2) + \sum_{k=1}^z (2n_k\bar{n} - \bar{n}^2) = \sum_{k=1}^z (n_k - \bar{n})^2 + z\bar{n}^2$$

Substituted in equation (20) this gives:

$$\bar{t}_s = T_b + \frac{1}{2}t_u + \frac{1}{2}t_u \frac{\sum_{k=1}^z (n_k - \bar{n})^2 + z\bar{n}^2}{z\bar{n}}$$

$$\bar{t}_s = T_b + \frac{1}{2}t_u(\bar{n} + 1) + \frac{1}{2}t_u \frac{\text{Var}(n_k)}{\bar{n}} \quad (21)$$

9. Delay time as a component of transit time

9.1 Introduction

If the volume of traffic is small, all the vessels can pass through the lock together in the next lockage. The delay experienced is then equal to the transit time when navigation proceeds without interruption ($t_p = t_w + t_s$).

If the volume of traffic increases, the situation will arise in which the number of vessels presenting themselves will be larger at certain times than the capacity. A proportion of the vessels cannot then be handled immediately but will have to wait until the next lockage. Any further increase in the volume of traffic will lead to an accumulation of vessels in the lock approaches. This excess will be cleared in the periods when the volume of traffic is less than the capacity.

It will be obvious that the probability of delay occurring is partly dependent on variations in the volume of traffic. The volume pattern must therefore be subjected to closer examination.

Variations in the volume of traffic are partly systematic and partly stochastic in character. The systematic structure is largely determined by 24-hour and weekly cycles. The 24-hour cycle is characterised by a relatively low volume of traffic at night and a relatively high volume in the daytime. The weekly cycle shows itself in the fact that 24-hour volumes of traffic are greater in the periods from Monday to Friday than on Saturday and Sunday. The hours of operation of a large number of locks in the Netherlands are varied to take into account these volume cycles by closing them for a period during the night and reducing the number of hours of operation at weekends.

The delay time of vessels is determined with the aid of a simulation of the lockage process. Such a simulation is in fact a method of computation in which lockage is simulated in accordance with a particular schema.

In view of the occurrence of weekly cycles in traffic volume the obvious procedure is to carry out a lockage simulation for a period of one or more whole weeks. By repeating the simulation for several different volumes of traffic it is possible to determine the relation between the average delay time per vessel and the volume of traffic. The latter quantity is generally stated in relation to the lock capacity.

The end product of a series of lockage simulations is the 'delay curve', which shows the relation between the average delay time per vessel (\bar{t}_0) and the volume-capacity ratio on a weekly basis (I_w/C_w).

As a result of the big differences in day and night volume and the stochastic nature of the volume pattern delays will be experienced by vessels even for quite low values of

I_w/C_w . In the case of many locks occasional vessels may be delayed when $I_w/C_w = 0.5$. As the value of I_w/C_w increases, so does the number of vessels delayed and consequently the average delay time per vessel (Figure 15).

As already stated, the delay curve is determined by carrying out lockage simulations for several different values of I_w/C_w . A volume pattern must be ascertained for every value of I_w to be applied. This is gone into in greater detail in Section 9.2. The lockage simulation itself is dealt with in Section 9.3.

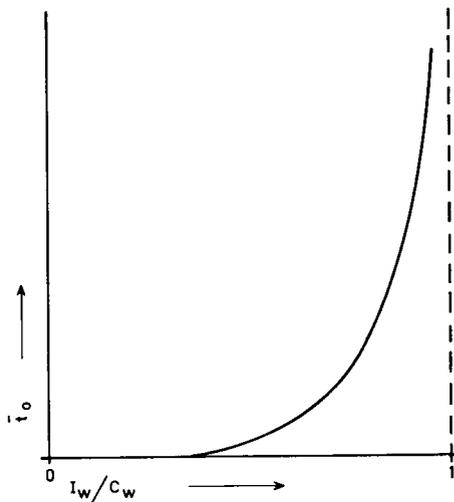


Figure 15. Graph showing the general relation between the average value of the delay time in hours (t_0) and the volume-capacity ratio (delay curve).

9.2 The generation of traffic volume patterns

The traffic volume patterns to be applied play an important role in the determination of the average future delay time per vessel by means of lockage simulations. The ascertainment of such patterns is, however, a matter of judgment, since there can be no getting away from the fact that future navigation trends are subject to many uncertainties.

Traffic volume patterns can probably be derived best from observed patterns. This is certainly true of existing waterways, for example where locks are to be replaced or enlarged. In the case of new waterways too, it will generally be better to use the volume patterns of an equivalent existing waterway as a starting point rather than patterns based entirely on conjecture.

The lockage simulation discussed in the remainder of this section is carried out on an

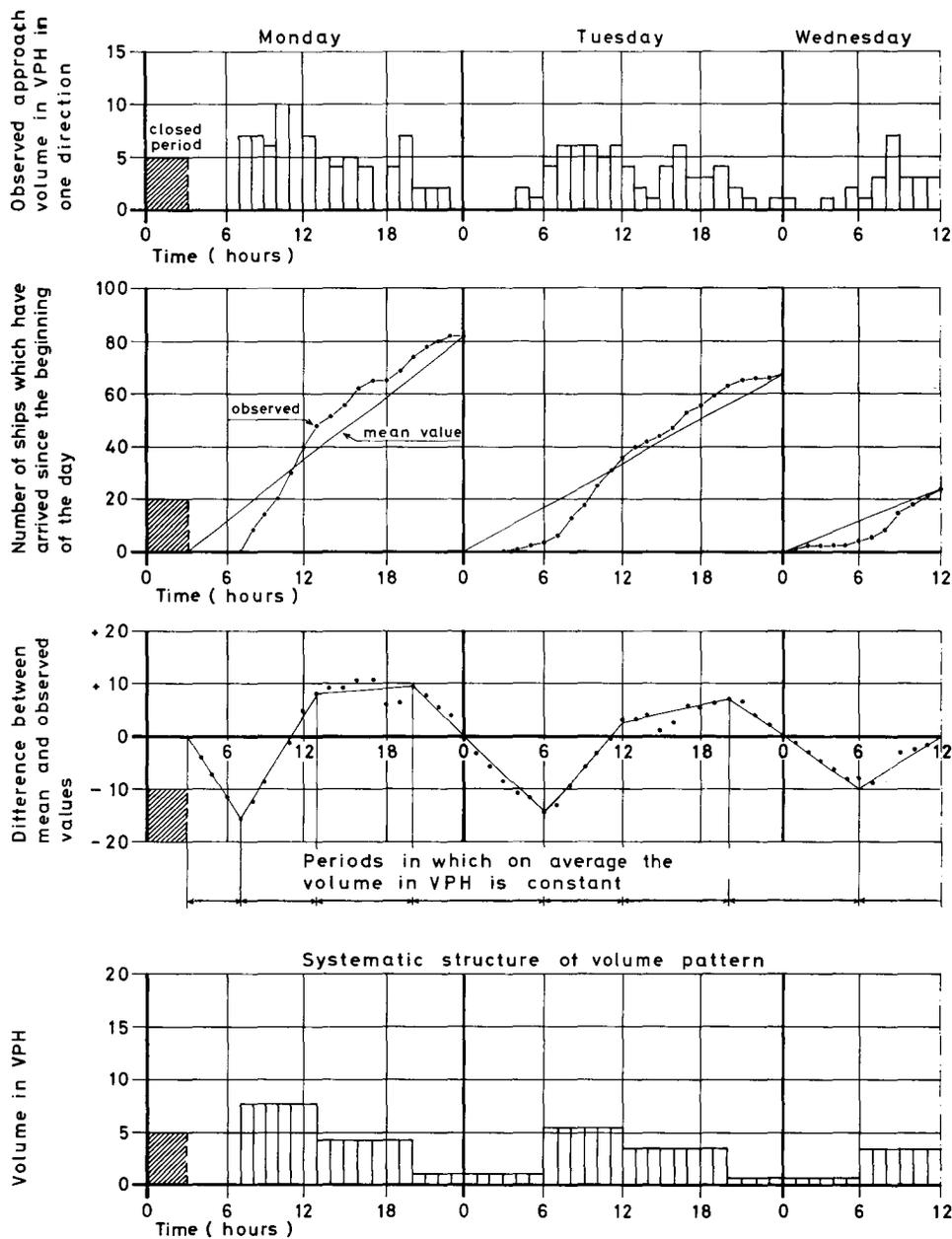


Figure 16. Determination of the systematic character of an observed volume pattern.

hourly basis. Consequently volume patterns constructed from hourly volumes are used as the starting point.

The following method can be used to generate derived traffic volume patterns.

1. An observed volume pattern per direction of navigation comprising one or more whole weeks (weekly cycles running from Monday to Sunday inclusive) has been used as a starting point. The value of I_w (vessels per week) is determined per week. It is perhaps unnecessary to repeat that the hourly volume is the number of vessels arriving at the lock per hour and not the number passed through the lock.
2. Determine the systematic structure of the volume pattern observed per direction of navigation, distinguishing between the following cases:
 - a. The composition of the vessel mix passing through (in deadweight tonnage categories) does not exhibit any systematic variations over a period of 24 hours or over the week.
 - b. Systematic variations do occur. In practice this is certainly the case with push-tows, which operate to a much greater extent on a continuous service basis than do the normal motor vessels and towed barges.

A customary method of determining the systematic character of the volume pattern in case a. is shown in Figure 16. If a long series of observations is available the systematic structure can be made apparent by determining the average volumes for the same hours on corresponding days (e.g. the same hour on a number of Mondays).

In case b. the vessel mix is subdivided into the relevant categories. A volume pattern per category is then used as the starting point per direction of navigation, the same methods otherwise being applied as in case a.

3. Draw up a forecast for the future development of the systematic structure of the traffic arriving (e.g. relatively more traffic at night, a relative decline in traffic at the weekend, etc.).
4. Determine the systematic structure of the volume pattern for a new (usually bigger) value of I_w . If an unchanged structure is assumed, the volume for each hour (from Figure 16D) is multiplied by a constant factor. If the structure is modified several different multiplication factors will have to be used.
5. Determine the stochastic variation for each period of the systematic structure in which the hourly volumes have the same (average) value.

If arrival of the vessels at the lock can be said to be random, use can be made of the theoretical Poisson distribution to determine the stochastic variation. The method is as follows. The number of hours in which 0, 1, 2, 3 etc. vessels arrive at the lock is calculated as a percentage for the average value of the hourly volume per period, using the equation:

$$P(k) = \frac{e^{-x} x^k}{k!} \times 100\%$$

where x = average hourly volume (in the period considered)

k = number of vessels per hour

$P(k)$ = percentage of the number of hours in which k vessels arrive.

The successive hourly volumes are then determined by drawing at random from the distribution calculated.

An example of this method is given in Table 9.2 for $x = 4$ (vessels per hour) for a period of 5 successive hours.

k (vessels per hour)	≤ 1	2	3	4	5	6	7	≥ 8
$P(k)$ %	9	15	20	20	16	10	6	4
distribution $P(k)$ (cumulative)	0-8	9-23	24-43	44-63	64-79	80-89	90-95	96-99

Table 9.2 Application of the Poisson distribution for $x = 4$ vessels per hour.

Let us assume the first five numbers drawn at random are 27, 09, 80, 44 and 56; the successive volumes of traffic are then 3, 2, 6, 4 and 4 vessels per hour. The method just described cannot automatically be used if the arrival of vessels, due to disturbing influences, is not of a random character. This may, for example, be the case if the volume pattern is affected by the regulating effect of an adjacent lock in the same waterway. In that event it is better to use a normal distribution with a small spread as a starting point, or even an estimated empirical distribution. The method of drawing at random from the distributions should always be used.

9.3 Simulation of the locking process

For a given lock the duration of successive lockages varies in practice under the influence of the number of vessels to be locked and the actual exit and entry times per vessel. These quantities are not, however, constant but are in turn a function of such different variables as the volume of traffic, sizes of vessel, vessel utilisation, type of vessel, the way vessels are navigated, etc. A simulation of the locking process on the basis of the variable lockage time, taking into account all the important influencing factors, is extremely complicated. No computer program is so far available for an expanded simulation of this kind. A modest beginning has been made with developing one, but it will still be some considerable time before an adequate simulation program is operational.

At the moment a schematised locking process is used as a starting point for determining

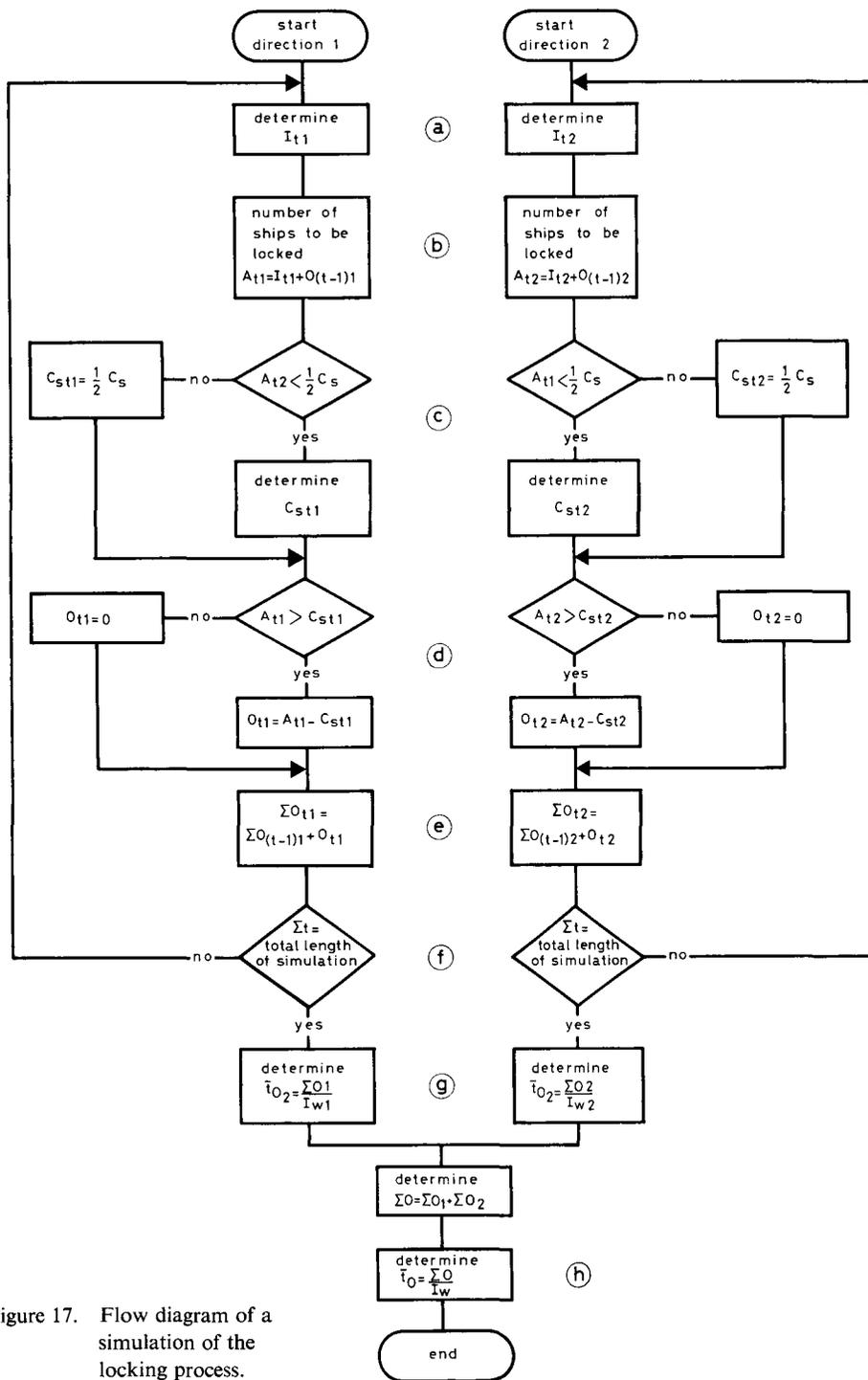


Figure 17. Flow diagram of a simulation of the locking process.

the delay times. The simulation of this process is carried out on an hourly basis. The vessel mix passing through the lock consists of unit vessels which are characterised by a deadweight tonnage that is equal to the average for all vessels involved in the simulation. The method used in this 'simple' simulation, which is carried out by hand for a period of a whole week (or several whole weeks), is as follows:

1. Calculation of the hourly capacity of the lock (C_s in VPH) as a function of the average deadweight tonnage (\bar{T}) and for a specified value of the vessel utilisation (λ) of the vessel mix (see Section 7.1).
2. Calculation of the weekly capacity (C_w) by multiplying C_s by the number of hours in operation (see 7.1).
3. Determination of a volume pattern per direction of navigation (see Section 9.2).
4. Calculation of \bar{T} and determination of the appropriate values of C_s and C_w .
5. Calculation of the weekly volume (I_w) from 3; a condition for carrying out the simulation is that $I_w/C_w < 1$.
6. Determination, in accordance with the diagram in Figure 17, of the total number of delay hours in the week under consideration. The following observations are made by way of clarification (the letters refer to Figure 17).
 - a. Only the hours when the lock is operational (t) are taken into consideration. The simulation begins with the first hour of operation on Monday and ends with the last hour of operation of that week. If there are periods when the lock is closed (e.g. for a number of hours at night), such periods are disregarded in the simulation and therefore in the determination of the delay times.
 - b. The number of vessels to be locked in hour t (A_t) is equal to the hourly volume (I_t) plus the vessels left over from the previous hour (O_{t-1}).
 - c. There are three possible ways of arriving at the number of vessels that are locked per direction in hour t . These are as follows:
 - $A_{t1} < \frac{1}{2}C_s$ and $A_{t2} < \frac{1}{2}C_s$
The capacity ($\frac{1}{2}C_s$ per direction) is bigger in both directions than the number of vessels to be locked; no vessels are, therefore, delayed.
 - $A_{t1} > \frac{1}{2}C_s$ and $A_{t2} > \frac{1}{2}C_s$
In this case a number of vessels are delayed on both sides of the lock.
 - $A_{t1} < \frac{1}{2}C_s$ and $A_{t2} > \frac{1}{2}C_s$ (or $A_{t1} > \frac{1}{2}C_s$ and $A_{t2} < \frac{1}{2}C_s$)
The capacity is not fully used in direction 1. Consequently lockage is quicker, with the result that the capacity in direction 2 increases. In this case, therefore, the capacity in one direction is a function of the number of vessels to be locked in the other direction. The relation between the capacity per direction (C_{s1} and C_{s2}) and the number of vessels to be locked in the opposite direction is different for each lock.
Equation (7) is used to calculate the capacity per direction. For the purposes of the simulation the calculated values are set out in a table, which may for example be arranged as follows: (Assume $C_s = 10$ VPH. The

minimum capacity per direction is then 5 VPH).

A_{t1}	5	4	3	2	1	0
C_{st2}	5.0	5.5	6.0	6.5	7.0	7.5

(C_{st2} is the capacity in hour t in direction 2).

The relation between A_{t2} and C_{st1} is shown in a similar table. There is no need in principle for the values of C_{st1} to be the same as the corresponding values of C_{st2} .

- d. The number of vessels to be locked is compared with the capacity in the direction under consideration. Where $A_t \leq C_{st}$ the number of vessel delay hours $O_t = 0$. Where $A_t > C_{st}$, $O_t = A_t - C_{st}$.
 - e. Determination of the total number of vessel delay hours (ΣO_t) up to and including hour t .
 - f. If the total number of simulated hours is smaller than the simulation period, the whole process is repeated with the following hourly volume.
 - g. When the end of the simulation period has been reached, the average delay time per vessel is determined per direction (\bar{i}_{o1} and \bar{i}_{o2}).
 - h. Finally the average delay time per vessel is determined for both directions together.
7. To enable the average delay time per vessel to be determined as a function of the volume-capacity ratio (I_w/C_w), the process is repeated several times from point 3 for other values of I_w . Four or five simulations are generally sufficient to enable the desired functional relationship to be ascertained.

Carrying out the simulation of the locking process just described by hand is a time-consuming operation, while in addition the chance of mistakes occurring in calculation is considerable. A computer program, completed in the first half of 1975, has therefore been developed, which enables a large proportion of the calculations to be performed by computer.

9.4 The relation between the average delay time per vessel and the variation in traffic volume

For a given lock the average delay time per vessel (\bar{i}_o) depends on the volume-capacity ratio (I_w/C_w) and the variation in traffic volume. If the deviations from the successive hourly volumes are generally small in relation to the average volume, \bar{i}_o will also be small even for relatively high values of I_w/C_w . The reverse is true where there are substantial variations in hourly volumes.

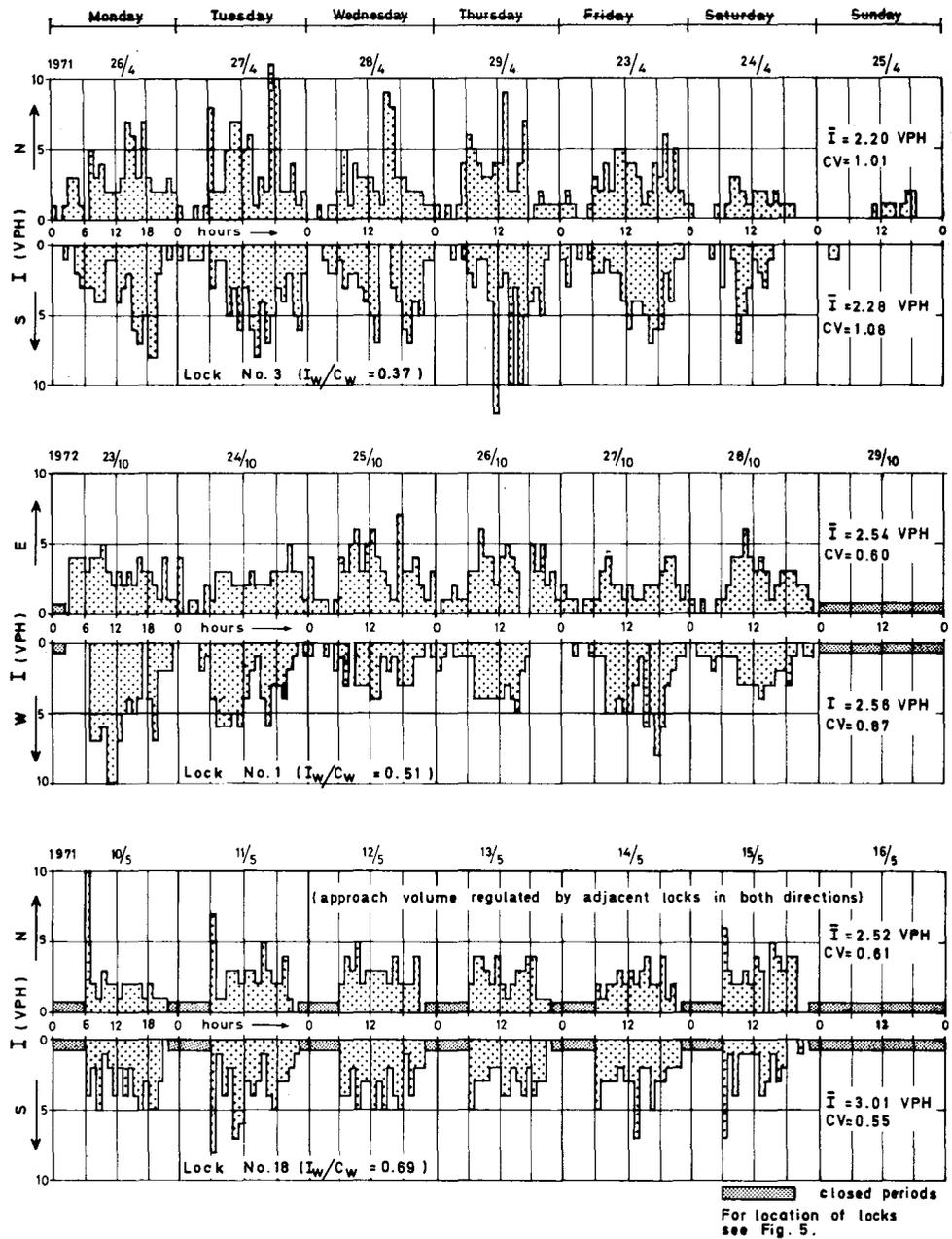


Figure 18. Observed volume patterns with different characteristics.

The *coefficient of variation (CV)* is used as parameter for the variation in traffic volume.

$$CV = \frac{\text{standard deviation of hourly volumes}}{\text{average hourly volume}} = \frac{S(I)}{\bar{I}}$$

Both $S(I)$ and \bar{I} are calculated over the number of hours per week that the lock is operational.

The value of CV is determined by both the stochastic and the systematic variations in the volume pattern.

The value of CV will generally decrease as the time the lock is operational is brought into line with the systematic structure of the volume pattern. This usually boils down

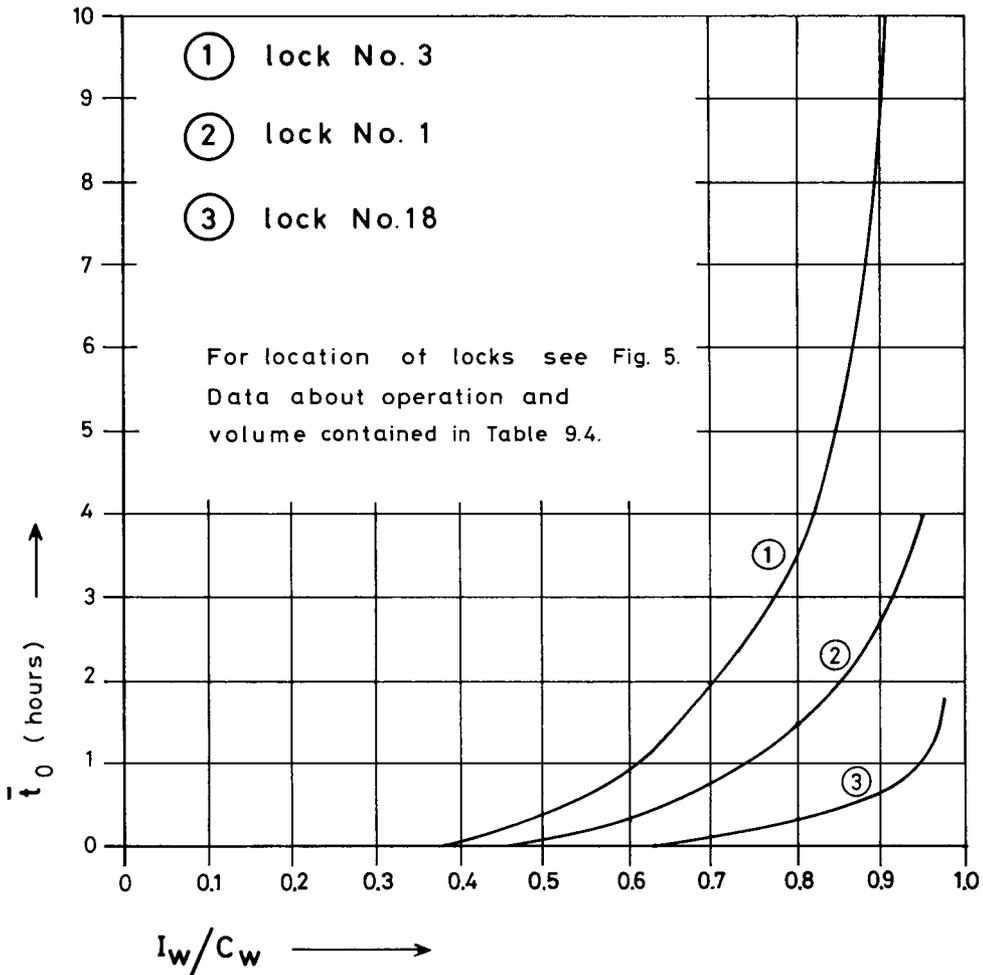


Figure 19. Delay curves for different conditions of volume pattern and lock location.

to adjusting the close period during the night and at the weekend, although the following must be noted:

- Since the weekly capacity decreases as a result of the institution of closed periods, the value of I_w/C_w will increase if the weekly volume remains the same.
- In the case of locks where there have been closed periods for many years, the volume patterns will have adjusted themselves to the operating times and not the other way round.

The introduction of closed periods in the case of an existing lock is therefore only justified where the value of the volume-capacity ratio is low (e.g. $I_w/C_w < 0.5$) and if, moreover, periods are selected during which the volume of traffic is indeed really small.

Stochastic variation of the volume of traffic will generally be small if there can be said to be regulation of traffic. This is so, for example, in the case of a canal with a large number of locks of approximately the same capacity and with the same hours of operation.

Figure 18 shows the volume patterns for three locks which differ from one another as regards operating times and location. Simulation has been used to determine the average delay times for these locks as a function of the volume-capacity ratio. The result is shown in Figure 19. The effect on the delay times of the coefficient of variation, calculated as the average value of the coefficient of variation for both directions of navigation, can be seen from Table 9.4.

Lock No. (Fig. 5)	Number of operating hours per week	I_w/C_w	CV	\bar{t}_0 (hours)
3	168	0.60	0.91	0.9
		0.75	0.86	3.0
		0.90	0.84	9.0
1	141	0.60	0.75	0.3
		0.75	0.72	1.0
		0.90	0.71	2.0
18	96	0.60	0.61	0.0
		0.75	0.55	0.2
		0.90	0.51	0.4

Table 9.4 Relation between volume-capacity ratio (I_w/C_w), coefficient of variation (CV) and average delay time (\bar{t}_0).



Photo 4. One chamber of the Volkerak lock operating at full capacity.

10. Practical applications

10.1 Relation between lock chamber dimensions and lock capacity

A number of capacity computations were made for the purpose of examining the effect of the lock width (B) on the lock capacity, the lock width being varied from 7 m to 16 m. The computations were made for several different lengths of lock (L). A number of results are given in Figure 20 for lock lengths of 80 m and 160 m. The main conclusion that can be drawn from these results is that locks with a width of less than about 12 m have a relatively small capacity. This is primarily the case where the average deadweight tonnage is small and arises from the fact that a wide variety of combinations of vessel beams are impossible with lock widths of between 8 and 11 meters.

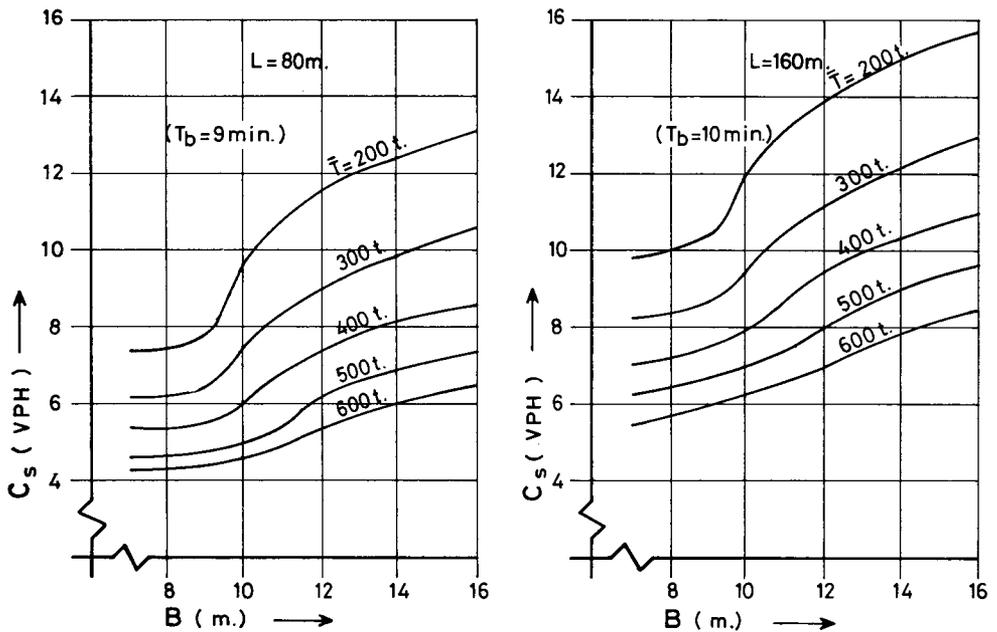


Figure 20. The lock capacity as a function of the width of the chamber (B).

The effect of lock length on lock capacity is illustrated in Figure 21. The assumption has been made in the computations that the operating time (T_b) increases, although

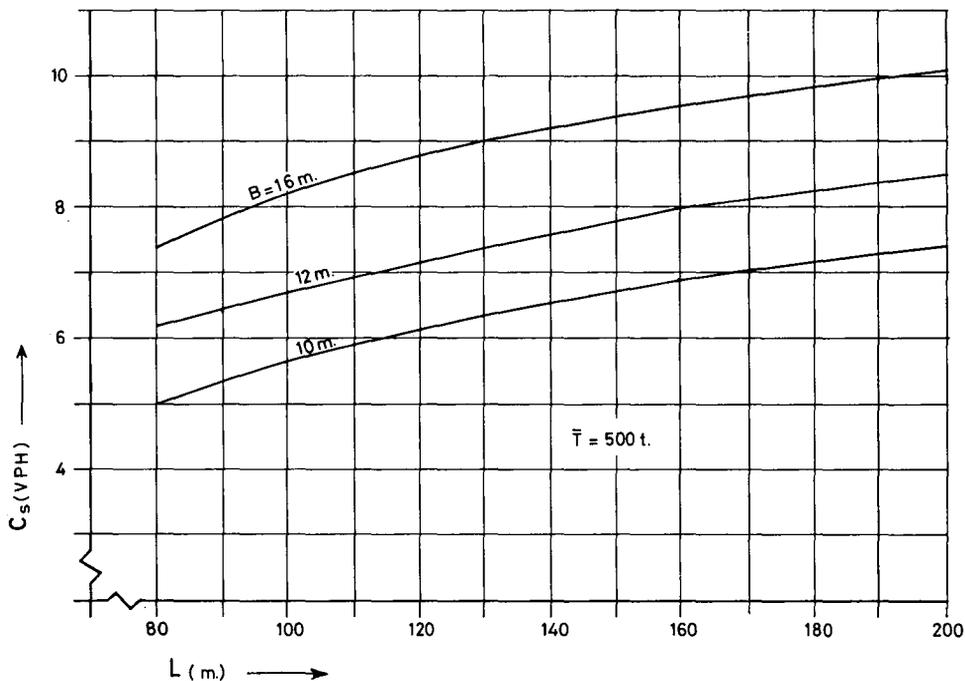


Figure 21. The relation between lock capacity (C_s) and the effective length of the chamber (L).

to a very small extent, with the length of the lock. The operating times for $L = 80, 120, 160$ and 200 meters are $9, 9.5, 10$ and 10.5 minutes respectively. It will be seen from the graph that the increase in lock capacity is not proportional to the increase in lock length. For a vessel mix with an average deadweight tonnage of $\bar{T} = 500$ tons the capacity of a lock with a width $B = 16$ m increases by 19% as L increases from 80 to 120 m. There is a gain in capacity of about 30% if L increases from 80 to 160 m and of about 36% if it increases from 80 to 200 m. The gain in capacity resulting from increasing the lock length is therefore clearly on a declining scale. Broadly speaking, the same is true for other values of both B and \bar{T} .

Three conclusions can be drawn from the foregoing:

1. The method used in lock designing in the past based on a lock capacity per sq.m. of lock surface area is incorrect and does not result in optimum lock dimensions.
2. A minimum lock width of 12 m is to be recommended. This also applies to busy waterways belonging to a low navigability class. This recommendation does not apply to locks primarily intended for pleasure cruising.
3. The employment of big lock lengths is not to be recommended from the point of view of capacity.

10.2 Deciding on the number of chambers

If the designer of a lock has to deal with a large volume of traffic, he is faced with the choice from the capacity point of view between one large chamber and two smaller parallel chambers. An example will show that a twin lock with chambers of relatively small dimensions can be better in many respects than a single chamber of relatively large dimensions. For this purpose the following comparison between two locks has been made.

	Lock I	Lock II
Number of (parallel) chambers	2	1
L (m)	120	240
B (m)	12	18
D (m)	4	4
Total surface area of lock (sq.m.)	2,880	4,320
T_b (min.)	10	12

It has been assumed that both locks are of modern design, as described in Section 4.1. The comparison between the locks relates to the capacity and average transit time of the individual vessel.

The capacity of the two chambers of lock I together is greater than that of lock II, as can be seen from Figure 22. While the difference diminishes as the value of the average deadweight tonnage increases, lock I clearly has the advantage up to $\bar{T} = 1,000$ tons.

As is shown by Figure 23, the twin lock with small chambers is also superior to the large lock chamber as regards the transit time of the individual vessel. Where the volume of traffic is low ($I_w < 800$ to 1,000 vessels per week) this is primarily attributable to the following two reasons:

- the locking cycle where the chamber is small is appreciably shorter than where it is large;
- in the case of a lock with two chambers the waiting time in accordance with equation (18) of Section 8.2 is given by $\bar{t}_w = \frac{1}{3}\bar{T}_c$; for a lock with a single chamber $\bar{t}_w = \frac{1}{2}\bar{T}_c$.

Where the volume of traffic is large lock II is inferior as a result of the smaller capacity, which means that the delay times in the case of this lock increase more rapidly than in the case of lock I.

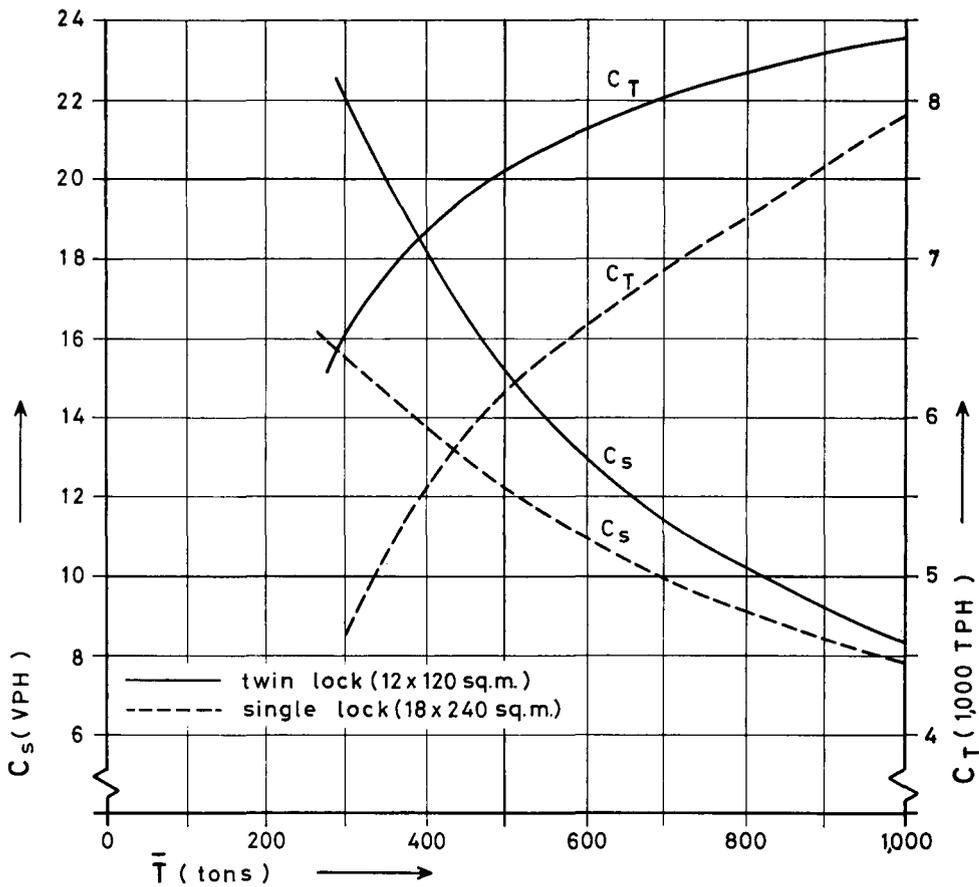


Figure 22. Comparison, based on lock capacity, between a twin lock with small chambers and a single lock with a large chamber.

It would be beyond the scope of this publication to extend the comparison between the two locks to such matters as building costs, manning, management, loss of water by lockage etc., which of course play an important role in lock design. The sum of the advantages and disadvantages of the two possibilities just outlined can be clearly illustrated by means of cost-benefit analysis. The unmistakable advantages for shipping of choosing a twin lock with relatively small chamber dimensions as opposed to a single large lock chamber should then, however, be among the factors taken into consideration.

10.3 The maximum admissible annual volume of traffic

Forecasts of traffic are generally drawn up on an annual basis. The concept of the

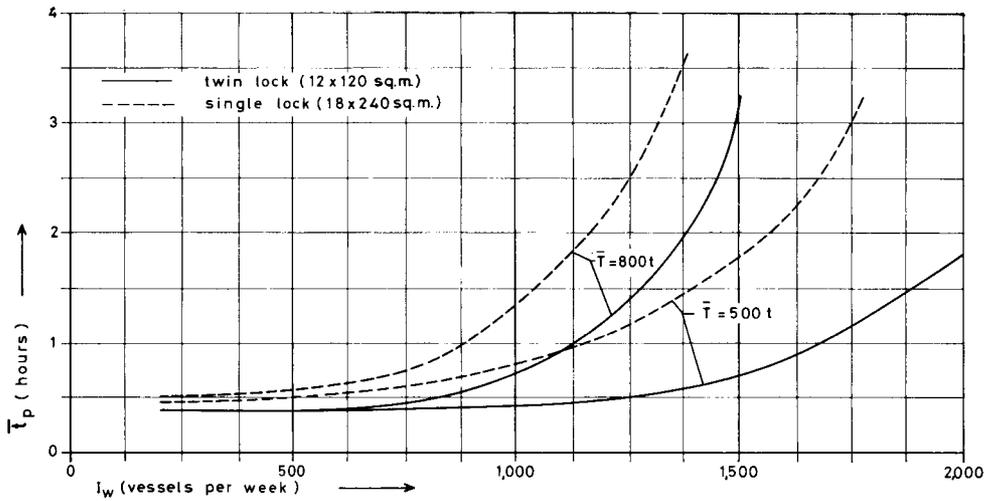


Figure 23. Average transit time per vessel (\bar{T}_p) in relation to the weekly volume (I_w) in the case of a twin lock with small chambers and a single lock with a large chamber.

admissible annual volume of traffic (I_a) has been introduced for the purpose of examining whether an estimated annual volume can be handled by a lock without undeniably long transit times occurring at certain times of the year. The ratio of annual traffic volume occurring and maximum admissible annual traffic volume I_o/I_a indicates the extent to which traffic can increase further without giving rise to considerable delay losses.

The basis for the determination of the maximum admissible annual traffic volume is the delay curve, which is determined by simulation and gives the relation between the average delay time per vessel and the volume-capacity ratio on a weekly basis. This relation generally has the following characteristics:

- If $I_w/C_w < 0.40$ to 0.60 , then \bar{t}_o is small enough to be disregarded.
- A further increase in I_w/C_w to between 0.65 and 0.85 is accompanied by a gradual increase in \bar{t}_o .
- If the limit of $I_w/C_w = 0.65$ to 0.85 is exceeded, then \bar{t}_o increases rapidly. The lock will then constitute a bottleneck in the waterway of which it forms a part.

The weekly traffic volume corresponding to the last-mentioned marginal value of I_w/C_w can be regarded as the maximum admissible, since at that point a relatively small increase in I_w results in an appreciable delay to shipping.

The aforementioned marginal value of $I_w/C_w = 0.65$ to 0.85 is only a rough indication, which can be more accurately determined if the delay curve of the lock under consideration is known. In that event the simplest method is in practice to assume a maximum admissible value of \bar{t}_o of for example 0.5 to 1.0 hours and to regard the corresponding value of I_w/C_w as a marginal value.

The maximum admissible annual volume of traffic (I_a) is now determined as follows. A representative week is ascertained on the basis of the observed traffic volume fluctuations during the year. The traffic volume during this week is then expressed as a percentage of the annual volume. This percentage can now be used to convert the maximum admissible weekly traffic volume into the maximum admissible annual volume of traffic, it being customary to express the latter value in deadweight tons per year.

The choice of a representative week is to some extent arbitrary. Basing on the busiest week is not to be recommended, since it may be an exception. It is better, for example, to base on the busiest period of 4 to 6 weeks and to regard the average weekly traffic volume of this period as representative.

To obtain a rapid assessment of the utilisation of a lock in a specific case it is possible to base the computation of I_o/I_a on the rough marginal values of I_w/C_w as illustrated in Table 10.3. In the circumstances obtaining in the Netherlands it is broadly true to say that the weekly traffic volume averages 2.15% of the annual volume (for the average weekly traffic volume the figure is 1.92%). This percentage may, however, be considerably higher in the case of a large number of locks

Length of time lock operational (per week)	Marginal value of I_w/C_w	
	Random traffic volume	Batched traffic volume
168 hours (continuous operation)	0,65	0,75
140 hours approx. (continuous, closed on Sunday)	0,70	0,80
100 hours approx. (closed for periods at night and at weekends)	0,75	0,85

Table 10.3 A few (rough) maximum admissible values of I_w/C_w for different conditions.

A few indications can be given on the basis of the afore-mentioned figures of the admissible annual volume of traffic. $I_a = 30 \cdot C_w \cdot \bar{T}$ (deadweight tons per year) for a lock with no closed periods and with a random traffic volume pattern and normal seasonal fluctuations with regard to the distribution of the traffic volume over the year. If there are substantial seasonal fluctuations, then $I_a = 26$ to $27 \cdot C_w \cdot \bar{T}$. $I_a = 40 \cdot C_w \cdot \bar{T}$ (deadweight tons per year) for a lock with closed periods at night and at weekends, where traffic is regulated and normal seasonal fluctuations obtain. Finally it should be noted that the value of I_a is increasing in the case of many locks. The reason for this is the growth in the average deadweight tonnage of vessels, which is causing the capacity expressed in deadweight tons to increase.

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Appendices

I The vessel mix

(Data concerning deadweight tonnage categories and standard vessels)

No.	Dwt. tonnage category (metric tons)	Data on standard vessels				
		Dwt. tonnage (metric tons)	length (m)	beam (m)	draft (m)	$l \times b$ (sq. m)
0	50- 199	125	25	4.6	1.6	115
1	200- 449	325	39	5.1	2.3	200
2	450- 749	550	50	6.6	2.5	330
3	750-1,149	925	67	8.2	2.5	550
4	1,150-1,549	1,350	80	9.5	2.6	760
5	1,550-2,549	2,000	95	11.5	2.7	1,090
6	2,550-4,999	4,100	175	11.4	3.0	2,000
7	$\geq 5,000$	8,800	185	22.8	3.2	4,220

No.	Horse power	Max. wetted cross sectional area (sq.m.)		displacement (cu.m.)		
		laden*	empty	laden*	empty	
0	60	7.4	(6.5)	1.8	165	40
1	140	11.7	(10.4)	3.0	425	100
2	260	16.5	(14.6)	4.6	710	160
3	520	20.5	(18.4)	6.8	1,180	255
4	730	24.7	(22.4)	9.3	1,740	390
5	1,100	31.0	(28.8)	12.3	2,600	600
6	1,200	34.2	(30.0)	6.5	5,150	1,050
7	2,500	73.0	(64.0)	13.0	10,600	1,800

* Values between brackets relate to a deadweight tonnage utilisation of 0.85 per vessel.

Table 1. Data on deadweight tonnage categories and representative standard vessels.

\bar{T} (metric tons)	Proportion of standard vessels (%)							
	0	1	2	3	4	5	6	7
125	100.0	—	—	—	—	—	—	—
160	82.5	17.5	—	—	—	—	—	—
200	62.5	37.5	—	—	—	—	—	—
240	42.5	57.5	—	—	—	—	—	—
280	22.5	77.5	—	—	—	—	—	—
300	20.0	73.0	7.0	—	—	—	—	—
350	17.5	62.5	16.0	4.0	—	—	—	—
400	15.4	54.2	20.9	9.0	0.5	—	—	—
450	13.5	48.0	24.5	11.0	3.0	—	—	—
500	12.0	43.4	26.1	13.0	4.6	0.9	—	—
600	9.3	36.7	27.0	17.0	5.6	4.4	—	—
700	7.2	33.0	25.4	20.4	7.3	5.6	1.1	—
800	6.0	30.0	24.0	22.5	9.0	6.4	2.1	—
900	5.0	26.2	24.5	23.8	10.5	6.5	2.9	0.6
1,000	4.5	23.0	24.7	24.3	12.5	6.5	2.9	1.6
1,100	4.5	19.5	25.0	25.0	14.0	6.5	3.0	2.5
1,200	4.5	16.5	24.5	26.0	15.0	7.0	3.0	3.5
1,300	4.5	14.5	25.0	25.0	16.5	7.2	2.8	4.5
1,400	4.5	12.5	25.0	24.5	18.0	7.0	3.0	5.5
1,500	4.5	10.5	25.0	23.5	20.0	7.0	3.0	6.5

Table 2a Vessel mix in standard vessels for various average deadweight tonnages (T).
(Standard frequency distribution)

Note: If, for example, $\bar{T} = 600$ tons and the navigability class of the lock is 4, Table 2b should be used.

\bar{T} (metric tons)	Proportion of standard vessels (%)							
	0	1	2	3	4	5	6	7
A. Navigability class 4.								
500	12.0	42.0	27.0	13.0	6.0	—	—	—
600	8.5	32.0	31.0	17.0	11.5	—	—	—
B. Navigability class 5.								
700	7.0	29.0	27.0	22.0	8.0	7.0	—	—
800	5.0	24.0	25.0	25.0	10.5	10.5	—	—
900	4.0	18.5	23.0	27.0	13.5	14.0	—	—
1,000	3.0	14.0	21.0	28.0	16.0	18.0	—	—
C. Navigability class 6.								
1,000	3.0	22.0	24.0	26.0	11.0	8.0	6.0	—
1,200	2.0	16.0	22.0	29.0	11.0	10.0	10.0	—
1,400	2.0	10.0	19.0	32.0	11.0	12.0	14.0	—

Table 2b Alternative vessel mix in standard vessels for several 'lower' navigability classes (standard frequency distribution).

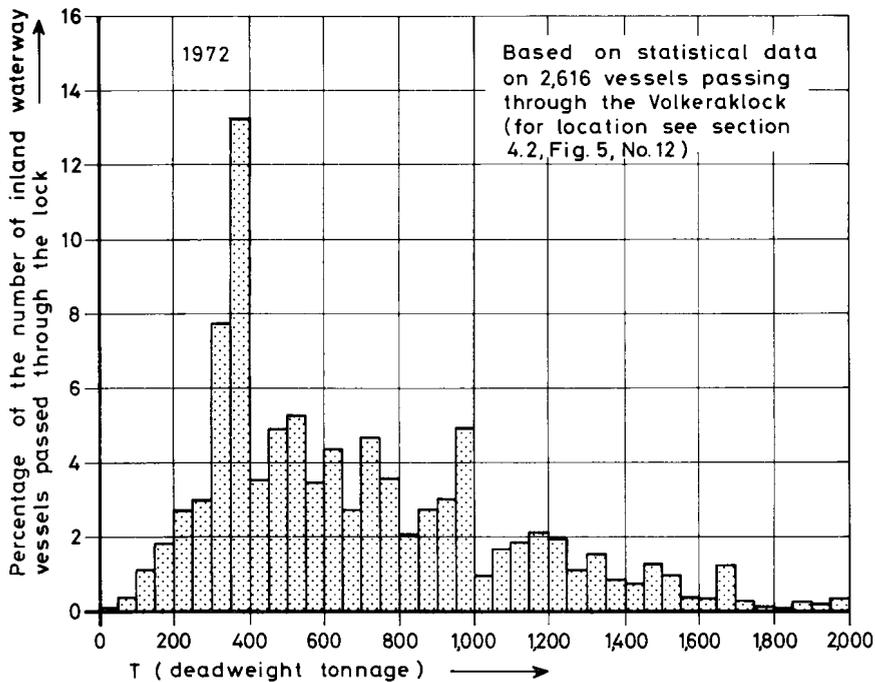
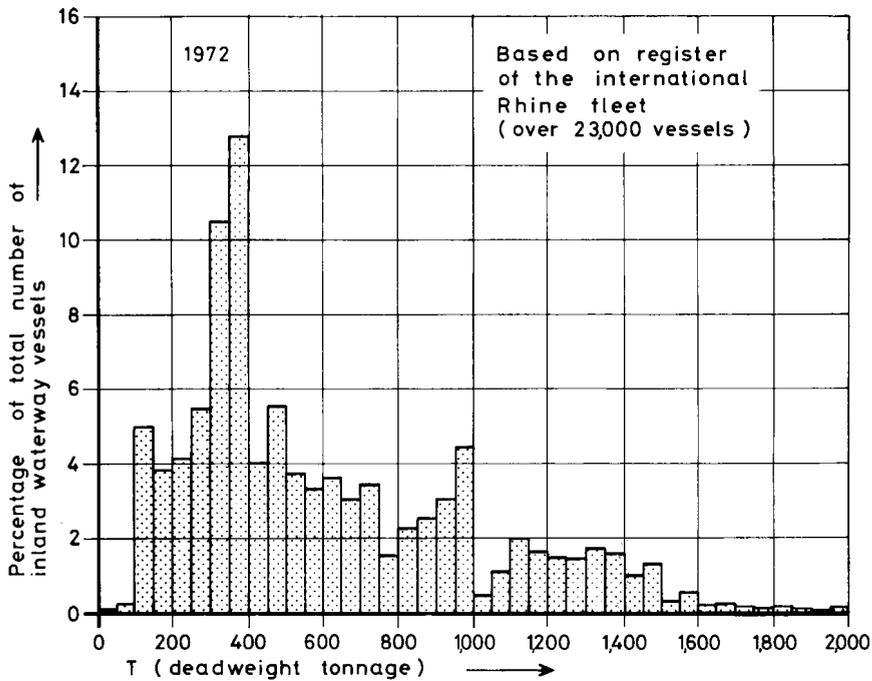


Figure 1. Impression of the vessel mix on the Dutch waterways (categories of 50 tons).

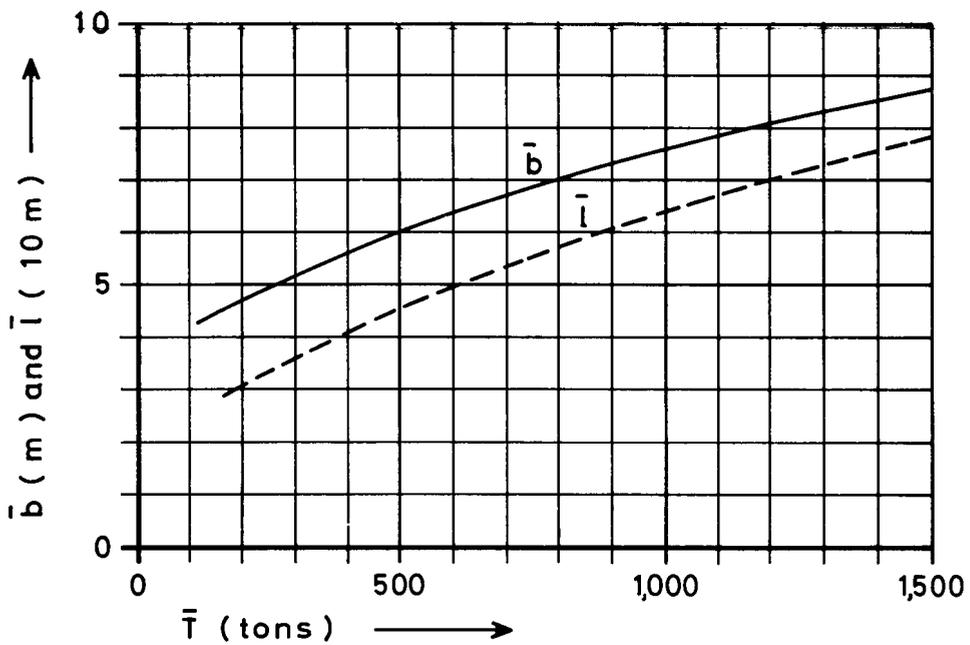


Figure 2. Relation between the average beam (\bar{b}) and length (\bar{l}) of vessels and the average deadweight tonnage (\bar{T}).

\bar{T} (metric tons)	S (metric tons)	Proportion of standard vessels (%)							
		0	1	2	3	4	5	6	7
300	64	12	88	0	—	—	—	—	—
	85	16	81	3	—	—	—	—	—
	105	20	73	7	—	—	—	—	—
	166	40	36	24	—	—	—	—	—
	189	50	17	33	—	—	—	—	—
500	141	0	30	65	5	0	0	—	—
	266	10	30	50	5	5	0	—	—
	332	12	43	26	14	4	1	—	—
	544	30	50	3	4	4	9	—	—
	592	50	20	11	5	2	12	—	—
700	285	0	20	35	39	6	0	0	—
	405	6	20	34	30	6	4	0	—
	582	7	33	25	20	8	6	1	—
	916	36	20	12	18	4	5	5	—
	1,094	40	30	11	4	2	5	8	—
1,000	480	0	10	14	46	24	5	1	0
	598	0	10	20	41	22	5	2	0
	1,234	5	23	25	24	12	7	2	2
	1,597	30	30	12	5	5	7	9	2
	1,918	38	30	12	3	3	2	8	4
1,500	792	0	9	10	11	26	40	4	0
	1,259	0	10	13	13	28	32	2	2
	2,118	4	11	25	23	20	7	4	6
	2,357	28	12	15	15	10	6	6	8
	2,654	57	6	5	5	5	5	7	10

Table 3 Different frequency distributions of standard vessels with the corresponding standard deviations (S in deadweight tons) for 5 different values of the average deadweight tonnage (\bar{T}).

No.	Deadweight tonnage categories (metric tons)	Standard ships		
		Dwt. tonnage (metric tons)	length (m)	beam (m)
0	50- 199	125	25	4.6
1	200- 349	320	39	5.1
1a	350- 399	370	47	5.1
2	400- 549	500	50	6.6
2a	550- 599	575	55	6.6
2b	600- 799	650	60	7.2
3	800- 999	900	67	8.2
3a	1,000-1,199	1,100	80	8.2
4	1,200-1,549	1,350	80	9.5
5	1,550-2,549	2,000	95	11.5
6	2,550-5,000	4,100	175	11.4
7	> 5,000	8,800	185	22.8

\bar{T} (metric tons)	Proportion of standard vessels (%)									
	0	1	1a	2	2a	2b	3	3a	4	5
200	62	33	5	—	—	—	—	—	—	—
240	43	50	7	—	—	—	—	—	—	—
300	22	60	8	9	1	—	—	—	—	—
350	18	52	10	9	4	4	2	1	—	—
400	17	43	10	14	3	6	3	2	2	—
500	13	29	10	18	4	11	6	5	3	1
600	10	30	5	17	4	9	9	7	5	4

Table 4 Vessel mix in standard vessels for different average deadweight tonnages (\bar{T}) in the case of subdivision into 12 deadweight tonnage categories.

II Graphs for use in determining vessel entry and exit times

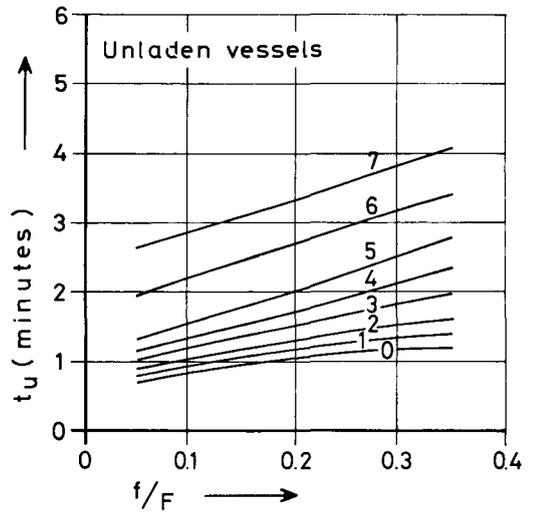
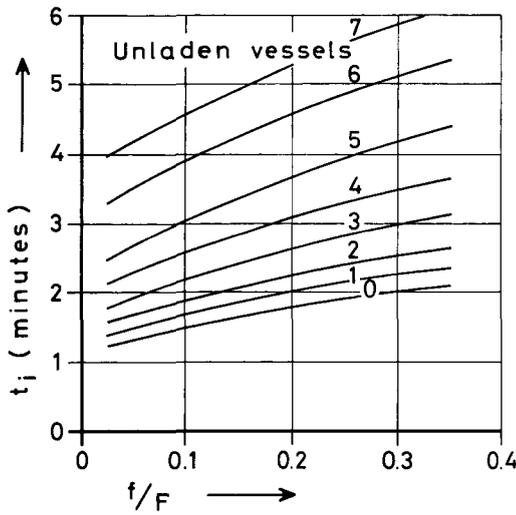
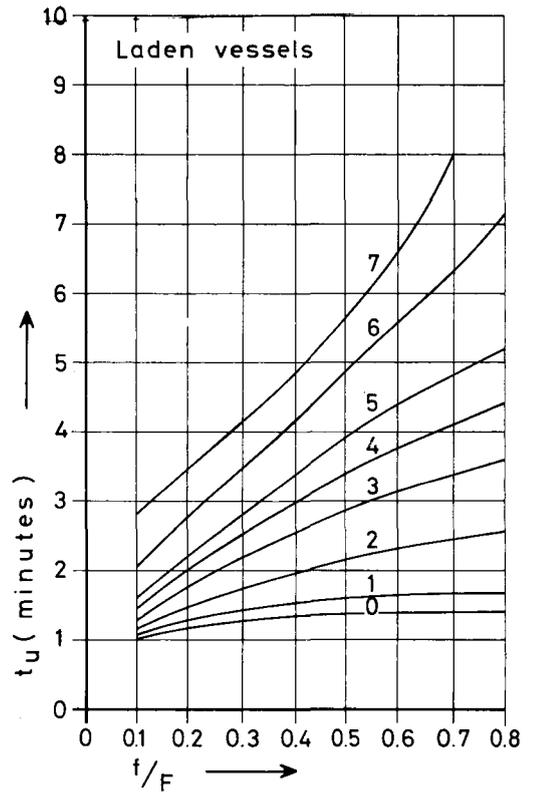
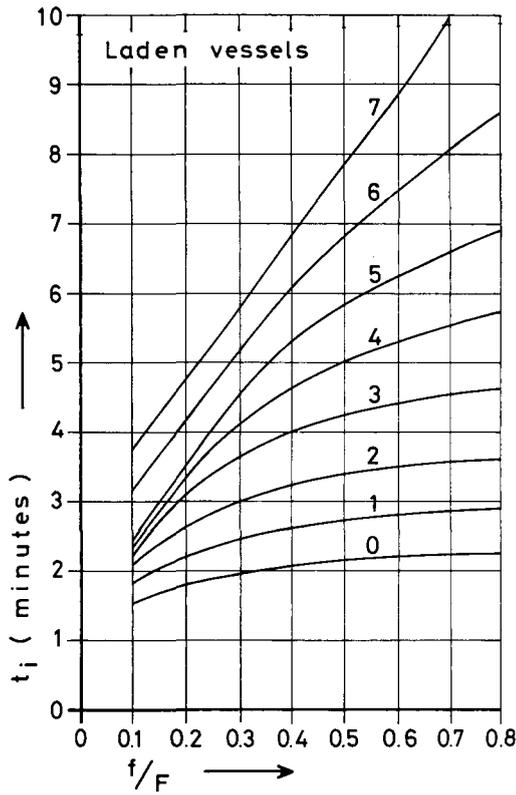


Figure 1. Entry and exit intervals of laden and unladen standard vessels.

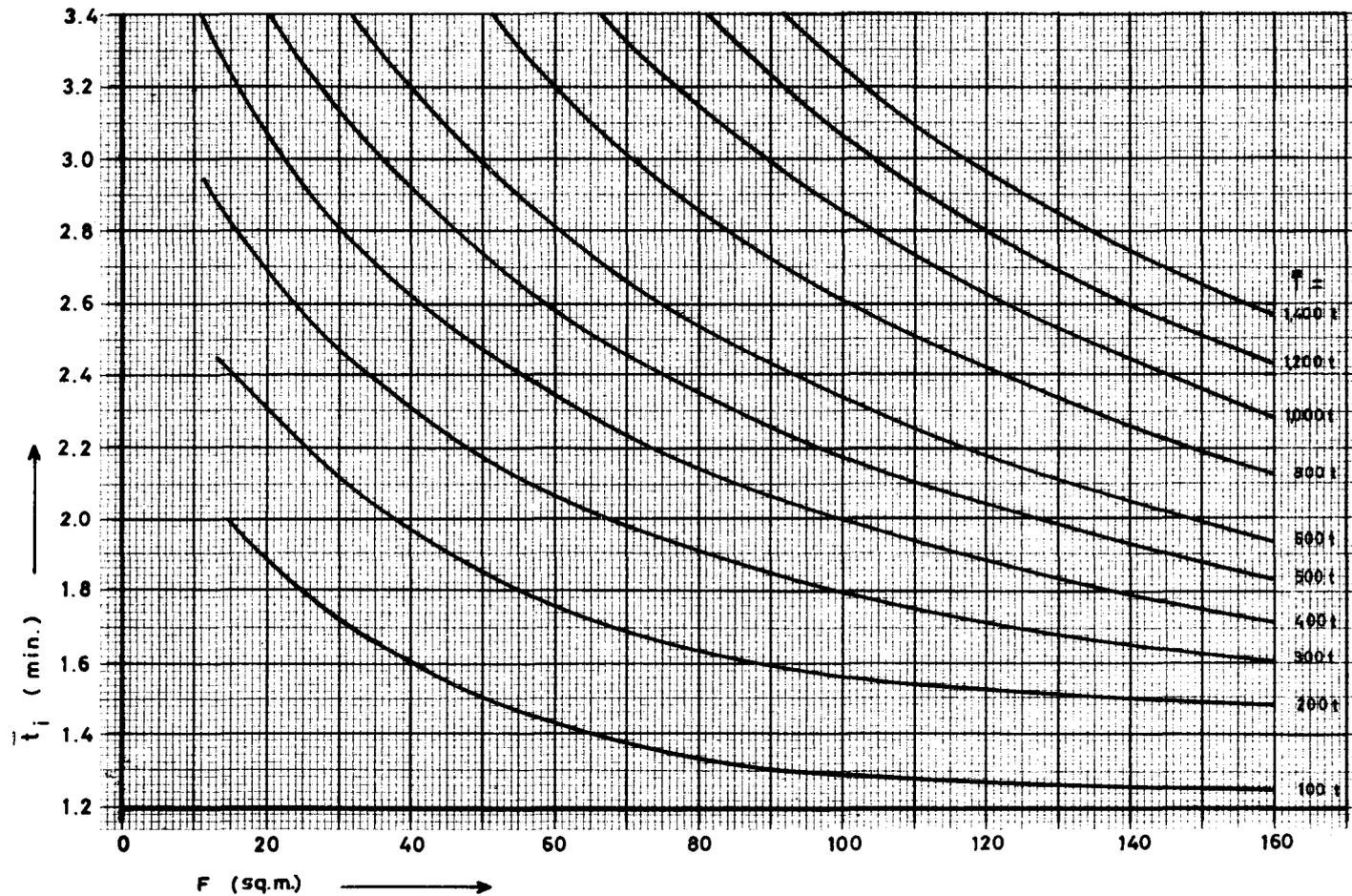


Figure 2. The relation between \bar{t}_i of laden self-propelled vessels and F for various values of \bar{T} .

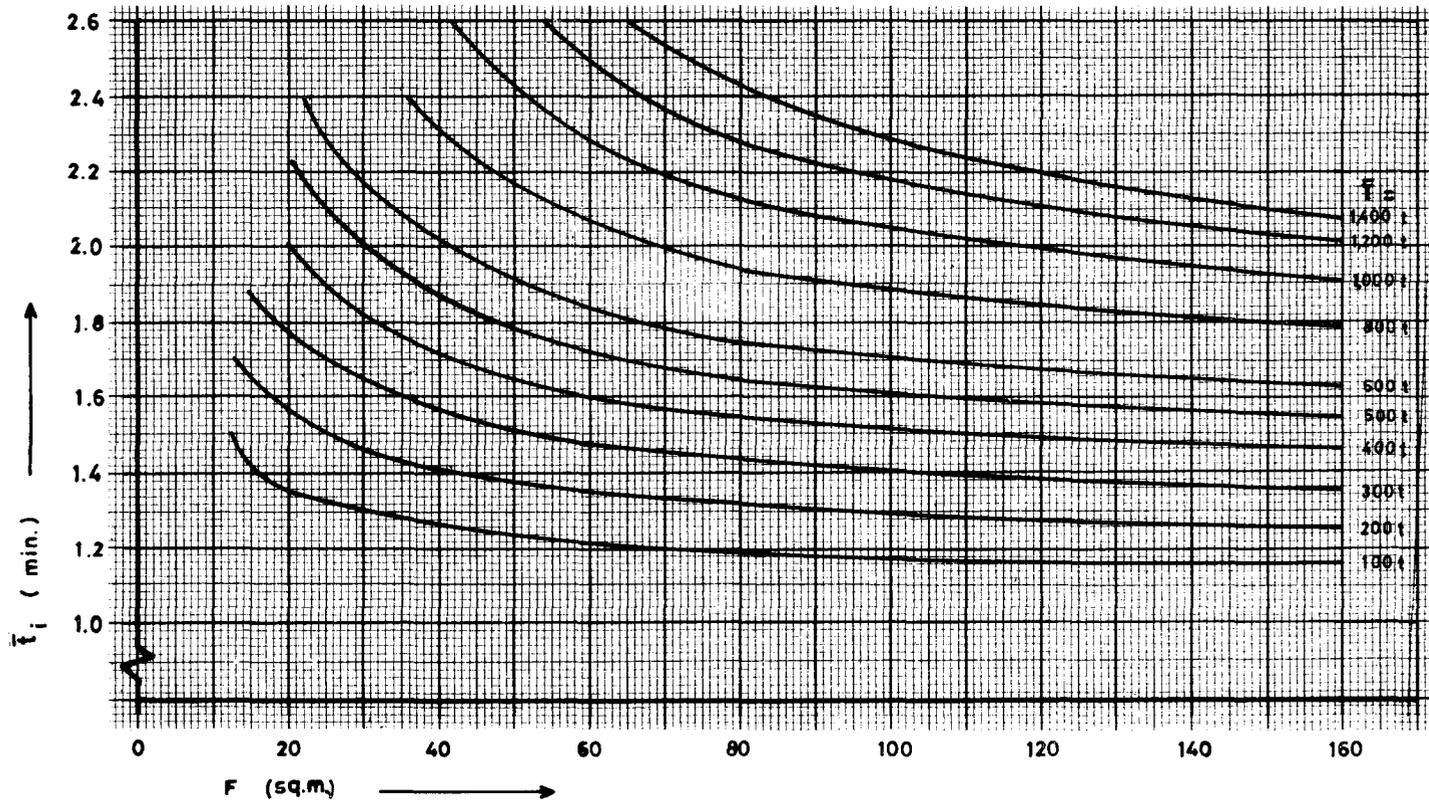


Figure 3. The relation between \bar{t}_i of unladen self-propelled vessels and F for various values of \bar{T} .

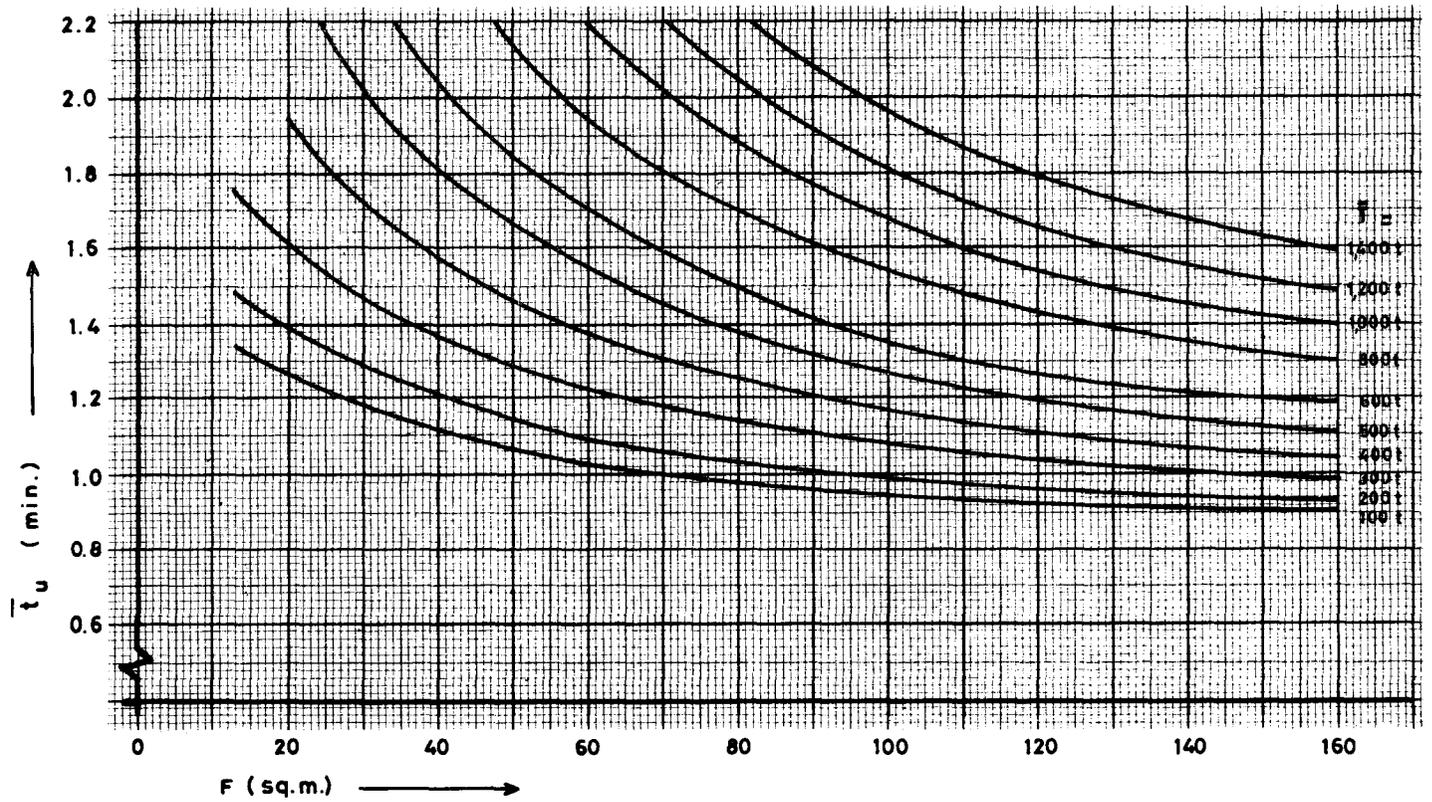


Figure 4. The relation between \bar{t}_u of laden self-propelled vessels and F for various values of \bar{T} .

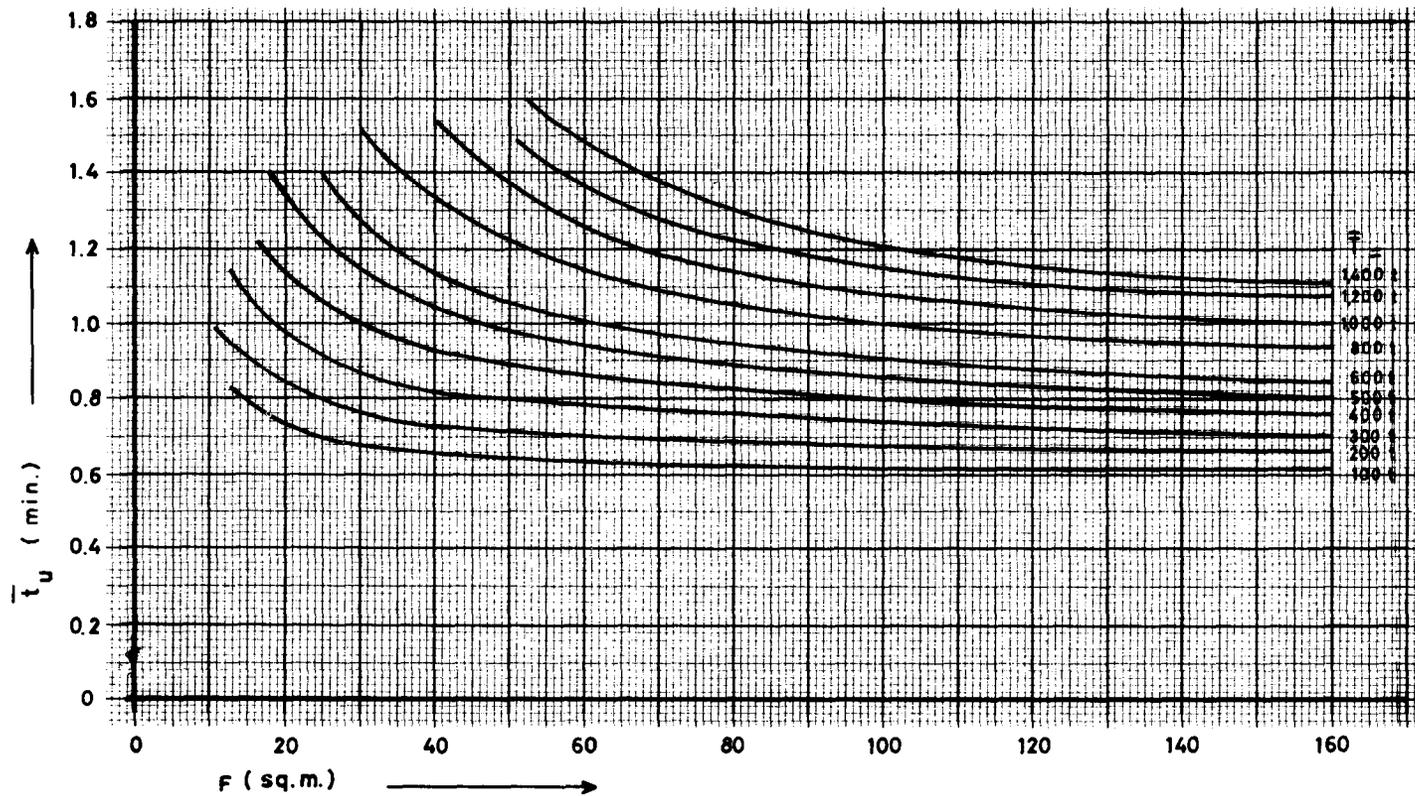


Figure 5. The relation between \bar{t}_u of unladen self-propelled vessels and F for various values of \bar{T} .

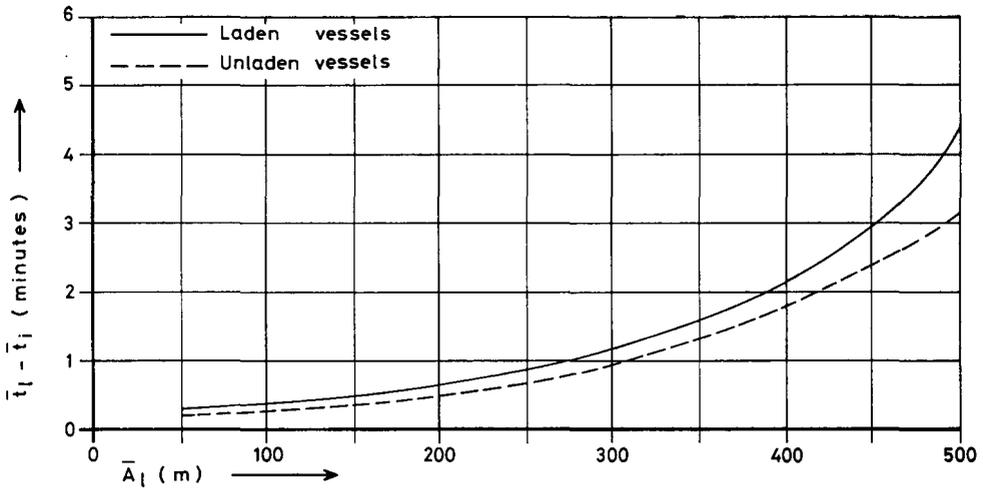


Figure 6. Correction graph for the average switch interval (\bar{t}_l).

III Graphs for use in determining the maximum number of vessels a lock chamber can hold

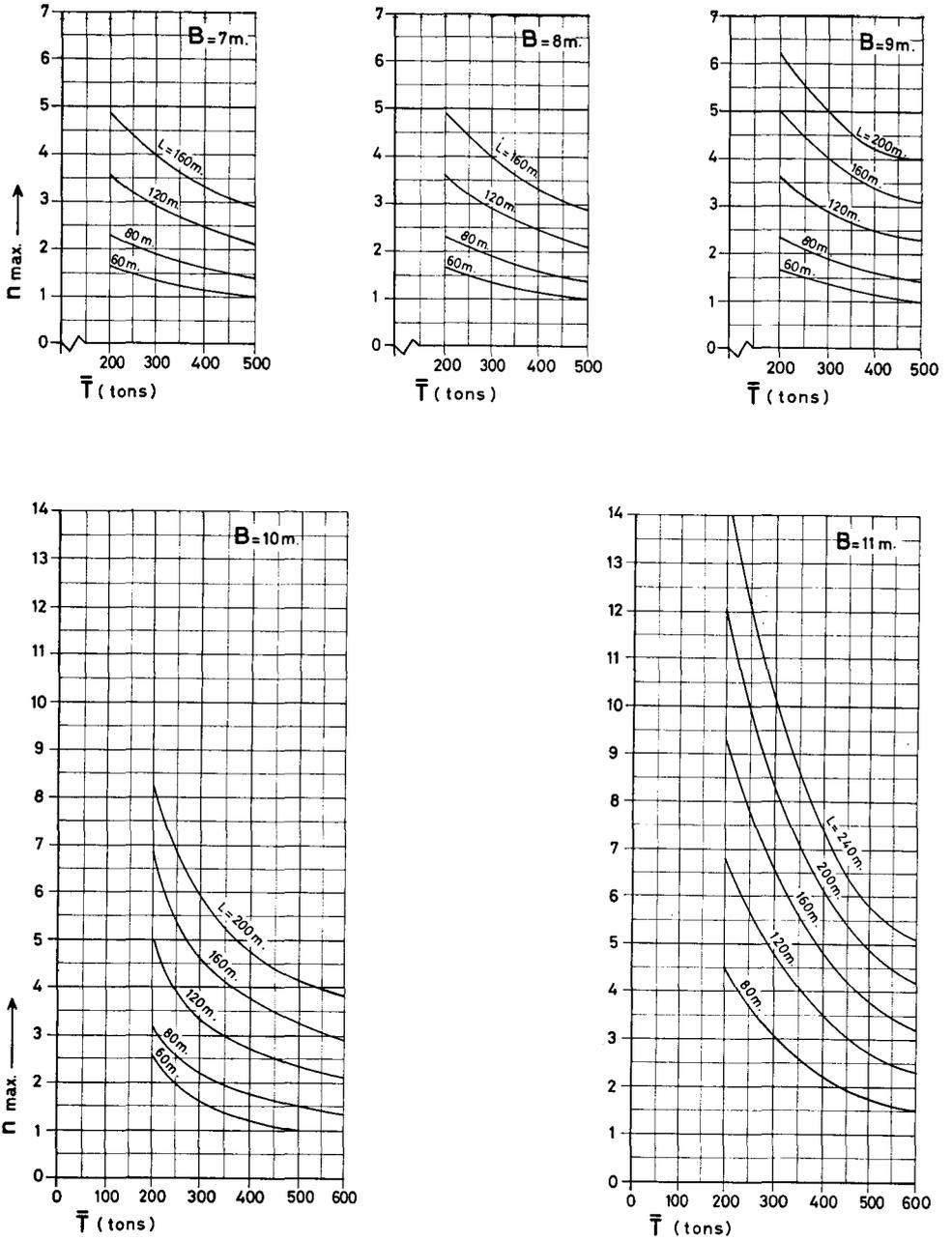


Figure 1. Maximum number of vessels the lock chamber can hold (n_{max}) as a function of the average deadweight tonnage (\bar{T}) for various lock dimensions.

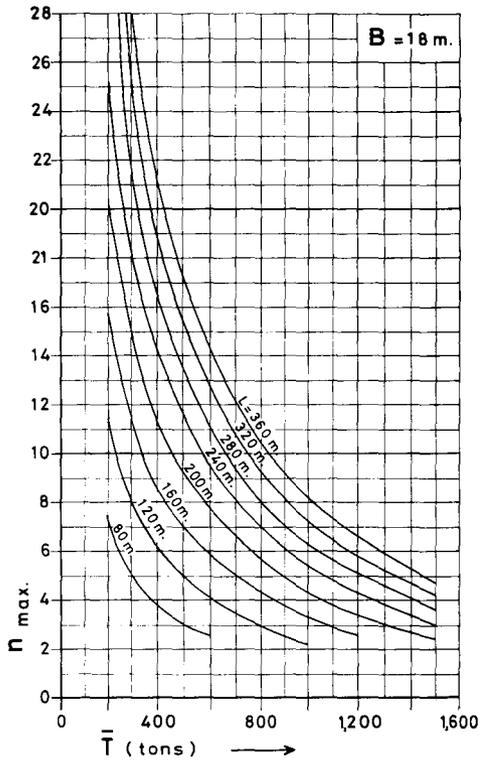
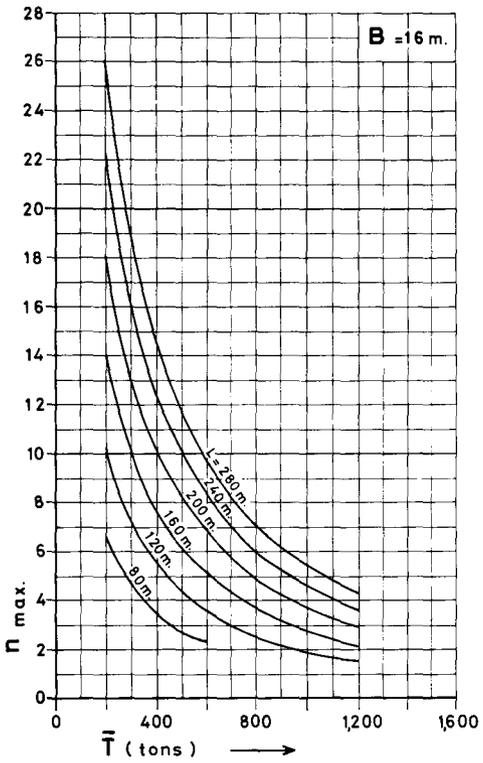
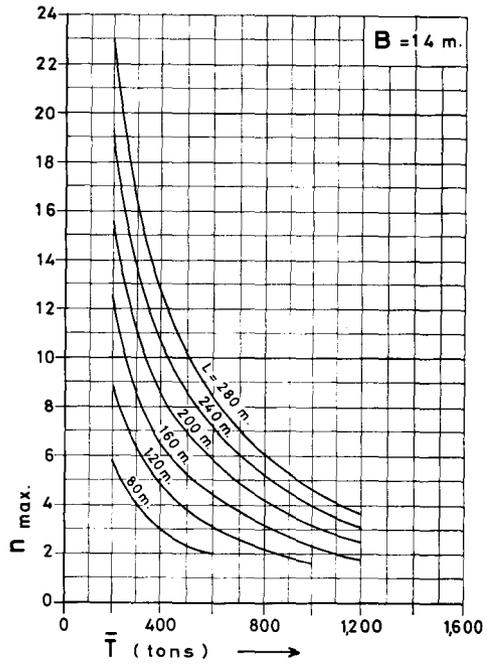
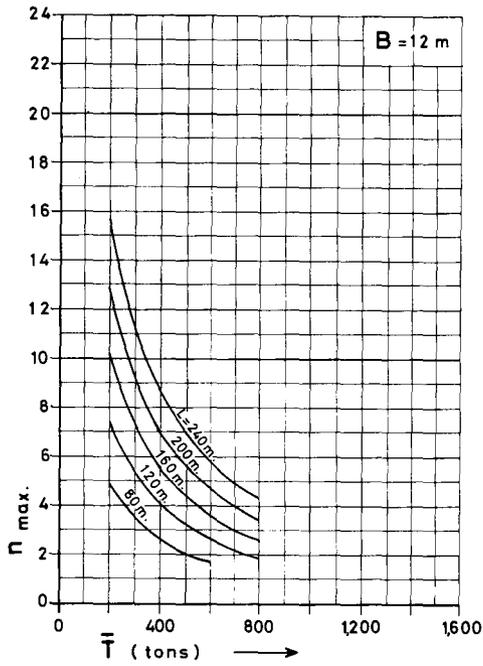


Figure 2. Maximum number of vessels the lock chamber can hold (n_{max}) as a function of the average deadweight tonnage (\bar{T}) for various lock dimensions.

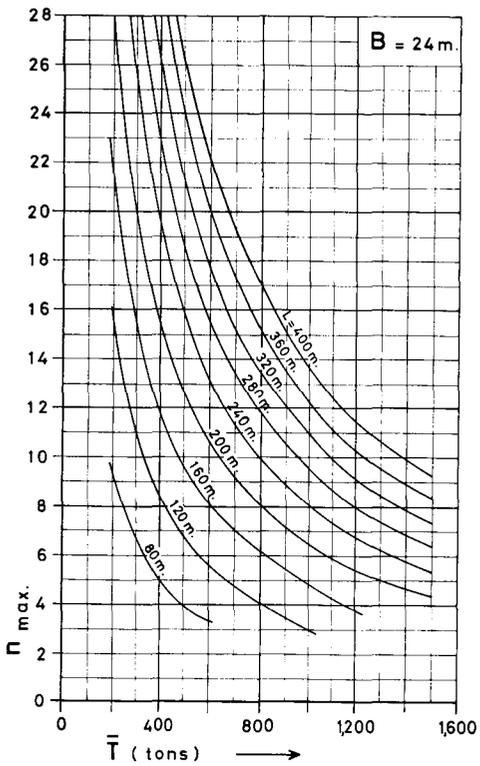
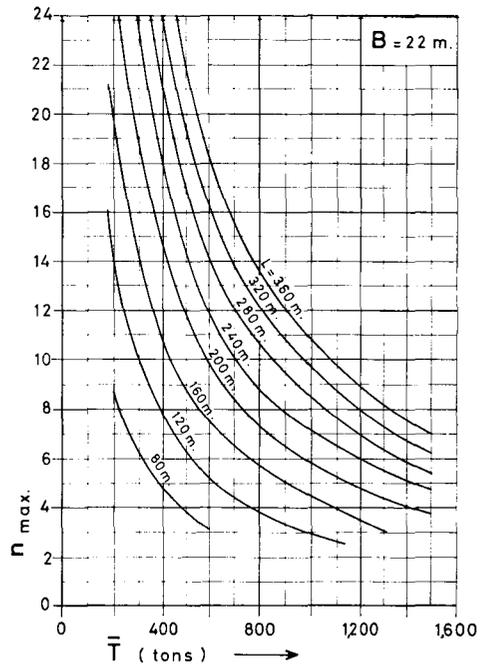
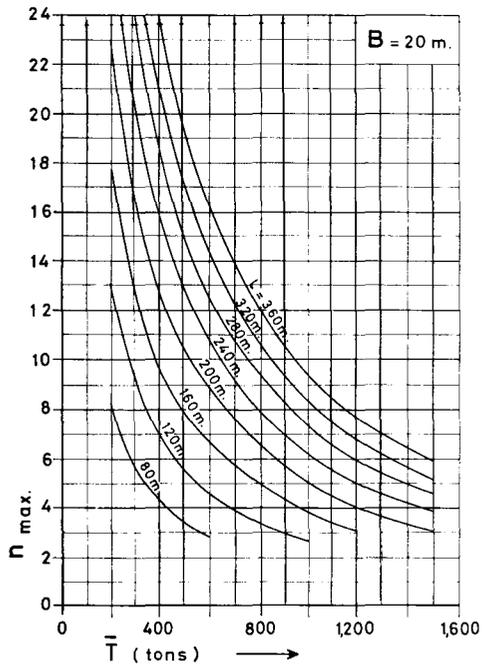


Figure 3. Maximum number of vessels the lock chamber can hold (n_{max}) as a function of the average dead-weight tonnage (T) for various lock dimensions.

IV Example to show the computation of the capacity and the maximum admissible annual volume of traffic for a lock measuring 16×142 sq.m.

General data on the lock

Navigability class: 5

Number of chambers $N = 1$

Modern shape (see Section 4.1)

Number of hours operational: 168 hours per week

Principal dimensions

$L = 142$ m	$D_u = 3.5$ m	$F_u = 56$ sq.m.	$\bar{A}_l - \bar{l} = 100$ m
$B = 16$ m	$D_l = 6.0$ m	$F_l = 96$ sq.m.	

Operating time

Filling or emptying chamber : 7.3 min.

Opening lock gates : 1.1 min.

Closing lock gates : 1.6 min.

T_b : 10.0 min.

General data on vessel mix:

Predominantly motor vessels.

In upstream direction $\lambda = 0.9$

In downstream direction $\lambda = 0.3$

Representative I_w is 2.15% of the annual volume of traffic

Table 1 Data relating to the lock and the vessel mix.

\bar{T} (metric tons)			200	400	600	800	1000
\bar{A}_l (m)			131	141	150	157	164
upstream	laden	\bar{t}_i	1.6	2.0	2.4	2.7	2.9
		\bar{t}_u	1.1	1.4	1.8	2.0	2.3
		\bar{t}_l	2.0	2.5	2.9	3.2	3.4
	unladen	\bar{t}_i	1.3	1.5	1.7	1.9	2.1
		\bar{t}_u	0.7	0.9	1.0	1.2	1.3
		\bar{t}_l	1.6	1.9	2.1	2.3	2.5
	$\lambda = 0.9$	\bar{t}_i	1.6	2.0	2.3	2.6	2.8
		\bar{t}_u	1.1	1.4	1.7	1.9	2.2
		\bar{t}_l	2.0	2.4	2.8	3.1	3.3
downstream	laden	\bar{t}_i	1.8	2.4	2.9	3.3	3.6
		\bar{t}_u	1.0	1.2	1.4	1.6	1.7
		\bar{t}_l	2.2	2.9	3.4	3.8	4.1
	unladen	\bar{t}_i	1.4	1.6	1.9	2.1	2.4
		\bar{t}_u	0.7	0.8	0.9	1.0	1.1
		\bar{t}_l	1.7	2.0	2.3	2.5	2.8
	$\lambda = 0.3$	\bar{t}_i	1.5	1.8	2.2	2.5	2.8
		\bar{t}_u	0.8	0.9	1.1	1.2	1.3
		\bar{t}_l	1.9	2.3	2.6	2.9	3.2

Table 2 Vessel entry and exit times (in minutes) for different values of \bar{T} . (\bar{t}_i and \bar{t}_u with the aid of Appendix II, Figures 2-5; $\bar{A}_l = 100 + \bar{l}$, for \bar{l} see Appendix I, Figure 2; \bar{t}_l with aid of Appendix II, Figure 6).

\bar{T} (ton)		200	400	600	800	1000
n_{\max}		12.2	6.6	4.4	3.1	2.4
upstream ($\lambda = 0.9$)	\bar{t}_l	2.0	2.4	2.8	3.1	3.3
	$(n - 1)\bar{t}_l$	17.9	11.2	7.8	5.5	3.9
	$n\bar{t}_u$	13.4	9.2	7.5	5.9	5.3
	T_b	10.0	10.0	10.0	10.0	10.0
	T_d	43.3	32.8	28.1	24.5	22.5
downstream ($\lambda = 0.3$)	\bar{t}_l	1.9	2.3	2.6	2.9	3.2
	$(n - 1)\bar{t}_l$	16.8	10.1	7.5	5.2	3.9
	$n\bar{t}_u$	9.8	5.9	4.8	3.7	3.1
	T_b	10.0	10.0	10.0	10.0	10.0
	T_d	38.5	28.3	24.9	21.8	20.2
T_c (min.)		81.8	61.1	53.0	46.3	42.7
C_s (VPH)		16.1	11.7	9.0	7.2	6.1
C_T (TPH)		3,220	4,680	5,400	5,760	6,100
C_w (vessels p. week)		2,637	1,916	1,474	1,179	999

Note: $C_s = 0.9 \times \frac{2n_{\max}}{T_c} \times 60$ (VPH),

$C_w = 163.8 \times C_s$.

Table 3 Computation of lock capacity (using computation method given in Section 7.1).

The maximum admissible annual volume of traffic

To calculate the maximum admissible annual volume of traffic (I_a) it is necessary to start from the delay curve. This is determined with the aid of a simulation of the locking process, as explained in Chapter 9. The carrying out of such a simulation is a time-consuming job. The values in Table 10.3 (Chapter 10) can therefore be used as a first approximation.

Assume that the traffic volume pattern has a random character (the traffic is not obviously regulated by adjacent locks whose capacity is equal to or smaller than that of the lock under consideration). It is further assumed that the lock is in operation continuously throughout the week.

A first approximation based on these assumptions is that the maximum admissible value of $I_w = 0.65 C_w$.

The representative $I_w = 2.15\%$ of the annual volume of traffic (I_a).

From this it follows that

$$I_a = 30.2 \times C_w \times \bar{T} \text{ (deadweight tons per year).}$$

\bar{T} (tons)	200	400	600	800	1,000
I_a (10^6 tons per year)	15.9	23.1	26.7	28.6	30.2

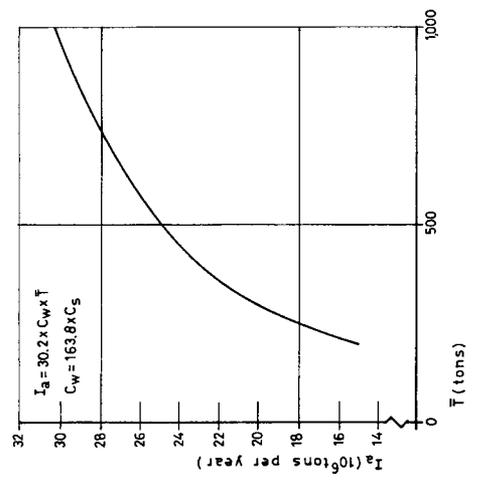
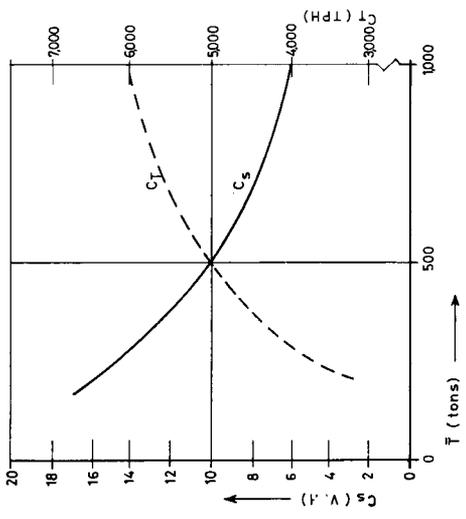
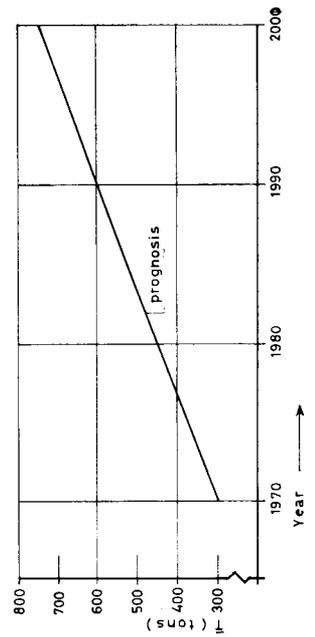
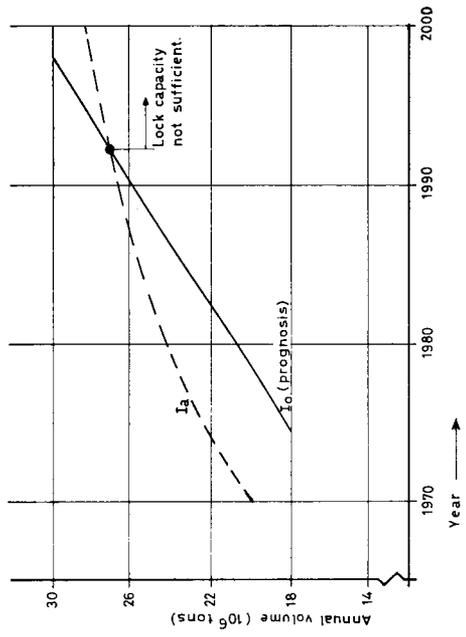
I_a can now be compared with a forecast which must relate to three figures:

1. goods traffic in tons per year.
2. the deadweight tonnage utilisation of the vessels and the percentage of empty vessels (λ)
3. the average deadweight tonnage of the vessels.

The deadweight tonnage to be handled is calculated for future years from 1. and 2. in tons per year.

3. is used to ascertain the value of I_a for future years.

An imaginary forecast is compared in the figure with I_a .



The capacity and the comparison of the expected and maximum admissible annual traffic volume of the lock under consideration (example of a method of presenting results).

Photographs:

Photo 1: KLM Aerocarto B.V.

Photo 2: Slagboom and Peeters

Photo 3: Rijkswaterstaat

Photo 4: Rijkswaterstaat

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