

Stockyard dimensioning for dry bulk terminals

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Abstract

Dry bulk terminals are used all around the world to handle large quantities of the bulk materials coal and iron ore. New dry bulk terminals have to be build or existing dry bulk terminals have to expand to facilitate the expected growing flows of bulk materials. The storage factor is proposed to dimension the terminal's stockyard and is the ratio between the annual throughput and the required storage area. Previous research showed that the storage factors of existing terminals vary considerably and in general do not correspond with the literature values. In this paper the storage factor is determined using discrete-event simulation. The storage factor predominately relates to the average storage time of the bulk materials at the stockyard, but also the terminal type, carrier tonnages and bulk material mix have to be considered while dimensioning the stockyard.

Keywords

Dry bulk terminal, stockyard dimensioning, storage factor, discrete-event simulation, storage time, interarrival time distribution, carrier tonnage distribution

1 Introduction

Dry bulk terminals are used worldwide as a buffer between incoming flows and outgoing flows of bulk solids materials (Lodewijks et al., 2009). Large bulk carriers sail between dry bulk terminals around the world to transport the bulk materials. This research is limited to just coal and iron ore. Figure 1 shows the arrival of one of the largest bulk carriers at the EMO import terminal in Rotterdam in June 2012. A dry bulk terminal consists of a quay wall where the bulk carriers are moored to be unloaded and a stockyard where the bulk materials are stored temporarily in piles. Huge machines are installed at the terminal to handle the bulk materials and belt conveyors are used to transport the bulk materials at the terminal.



Figure 1: The Vale Italia arrives at the EMO dry bulk terminal (Courtesy EMO)

Due to the growing demand for energy and steel new dry bulk terminals will have to be built and existing terminals are being forced to expand. However, there is an absence of a comprehensive and detailed design method for dry bulk terminals. Nowadays, it seems that designs are mostly based on rules of thumb and practical experiences. One of these rules of thumb is the storage factor [$t/m^2/y$], which is used to specify the required stockyard size, and is the ratio between the annual throughput [t/y] and the total storage area [m^2].

In this paper the storage factor will be determined as function of the terminal type, ship type and bulk material type. Stockyard dimensioning is essential during the (re)design of dry bulk terminals. An undersized stockyard will result in waiting times of ships, which is not allowed and cost the terminal operators money. An oversized stockyard makes it difficult to recover the huge investment costs.

2 Storage factor

Due to bulk density differences between coal (approximately 0.8 tons per cubic meter [t/m^3]) and iron ore ($2.6 [t/m^3]$), the required storage area per ton of bulk material differs. Suggested rules of thumb for the storage factor are for coal between 15 and 25 tons per square meter per year [$t/m^2/y$] and for iron ore between 30 and 40 [$t/m^2/y$] (Ligteringen, 2000).

The storage factors of 49 dry bulk terminals around the world were determined in a previous study (Van Vianen, et. al, 2011). In this research the values for the annual throughput for both coal and iron ore were based on the year 2008 and were derived from annual reports of dry bulk terminals or by interviewing terminal operators. The designated storage area for the bulk materials was examined and measured using Google Earth. Figure 2 shows the derived storage factors for import terminals and export terminals versus the annual throughput for coal as well as iron ore. The horizontal lines in these figures represent the limits suggested by Ligteringen.

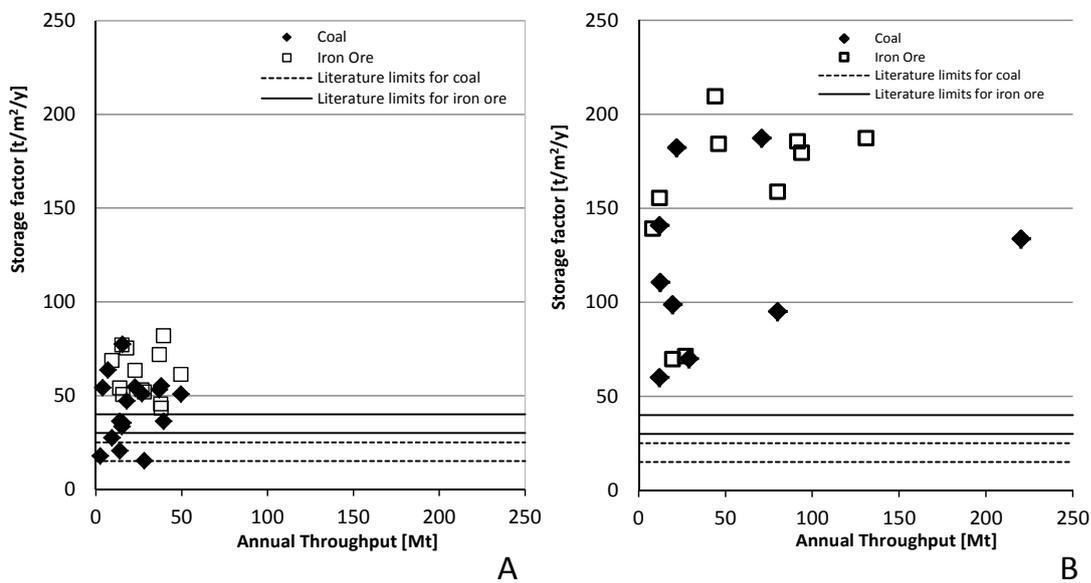


Figure 2: Storage factors for both import terminals (A) and export terminals (B)

From Figure 2 can be concluded that the storage factors of the investigated dry bulk terminals vary considerably and are much higher than the guidelines obtained from literature.

3 Parameters which determine storage factor

In this paragraph the parameters which determine the storage factor are presented (see Figure 3). This paper will determine the consequences of the bulk material, the carrier interarrival time distribution (more details are showed in paragraph 3.1), the carrier tonnage distribution (3.2) and the average storage time of the bulk materials at the terminal (3.3) on the storage factor. Future research will investigate the remaining parameters such as the storage policy (store all materials separately or group the materials with the same properties in one pile), storage time distribution (what happens if some piles are stored longer than others) and pile dimensions.

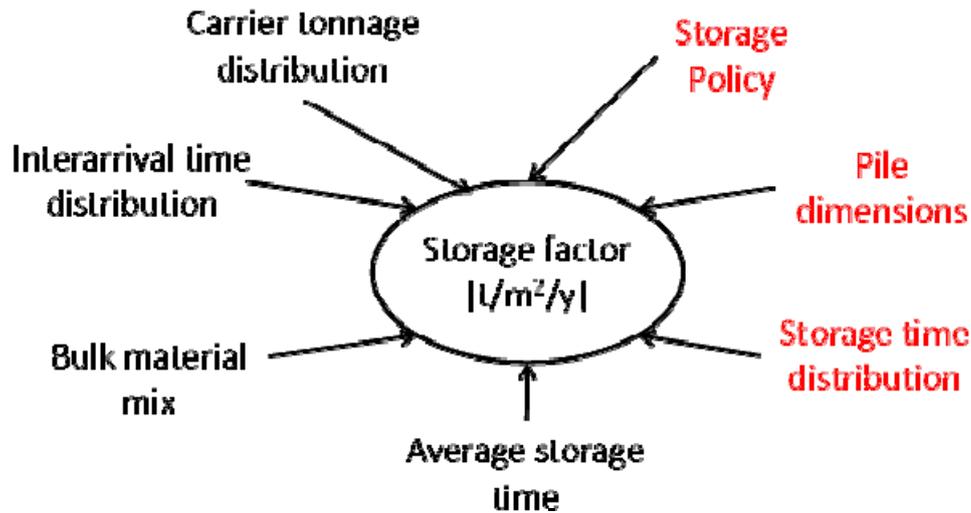


Figure 3: Parameters which determine the storage factor

3.1 The interarrival time distribution

The required storage area to store all materials is the product of the unbalance between the arrivals and departures at the dry bulk terminal. As already mentioned, bulk materials are transported between terminals by deep-sea bulk carriers. These ships do not generally arrive at their scheduled times because of bad weather conditions, swells and other natural phenomena during the sea journey as well as unexpected failures or stoppages (Jagerman and Altiok, 2003).

A previous study, (Van Vianen, et al., 2012), showed that the interarrival time distribution relates to the terminal type. At stevedoring import terminals, operators are not the owners of the bulk materials and have therefore less influence on the exact arrival time of the bulk carriers. For these terminals the interarrival time distribution can best be modeled with a negative exponential distribution. For a single-user import terminal (terminal which imports bulk materials for its own steel factory or power plant) an Erlang-2 distribution can be used to represent the arrivals of the bulk carriers. In an Erlang-2 distribution, the arrivals are more regular compared to the negative exponential distribution.

3.2 The carrier tonnage distribution

The above mentioned study showed also that especially stevedores are faced with a large variation of carrier tonnages, because these terminal operators unload ships for several clients. At single-user terminals, terminal operators plan the sizes of incoming ships more or less, which results in less variation in carrier tonnages (Van Vianen, et al., 2012).

3.3 The average storage time

For an import terminal, piles are formed from incoming bulk materials. A pile is reclaimed in smaller portions, which means that the occupied storage area for this pile decreases in time. The time between the creation of the pile and the time that the last remaining part of that pile is reclaimed, is called the storage time. When the

terminal's average storage time (because each pile can have its specific storage time) increases more stockyard area is needed to handle the same annual throughput.

To get some indication of the average storage time, real-world data of a Dutch stevedoring import terminal is examined. This data showed the storage times of 8,500 piles during 19 years of operation. From these data, a histogram is made (Figure 4A) to determine the average storage time and the distribution type. Figure 4B shows the average storage times per year during the 19 years.

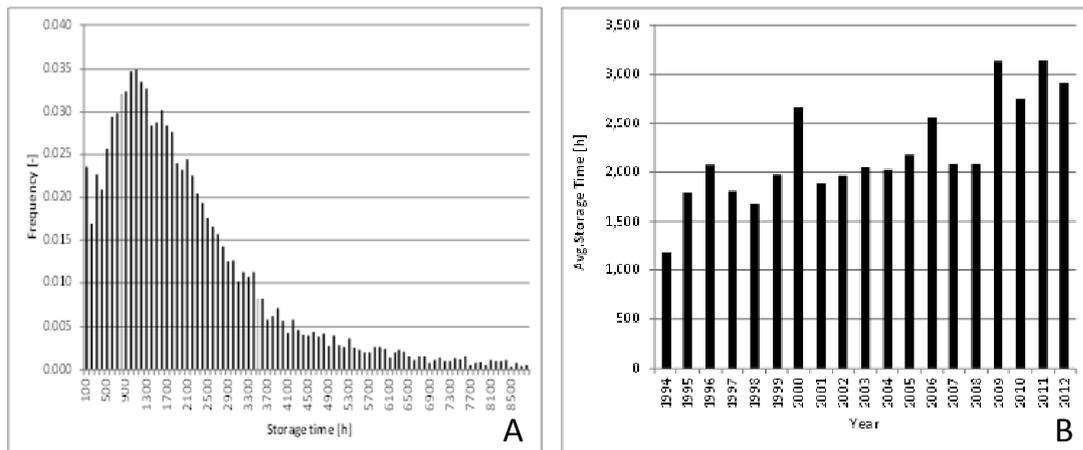


Figure 4: Storage time per pile (A) and average storage time during the years (B)

From Figure 4A can be concluded that the distribution of the piles storage time can be represented with an Erlang-2 distribution with an average value of 2,155 hours. Figure 4B shows that the average storage time varies during the investigated years but the trend of an increase of the average storage time can be seen as well.

4 Simulation-based approach

For the determination of the storage factor, a simulation-based approach is proposed. Dry bulk terminals have to deal with a lot of stochastic effects; the interarrival time of the ships and the carrier tonnages vary per arrival and the storage time can vary per pile. Besides, the operation at dry bulk terminals is too complex to grasp it in an analytical model. Another benefit of the simulation-based approach is the storage allocation, which means that storage locations at the stockyard are assigned to the piles and several allocation decisions can be modelled. For example, at import terminals piles are created from the imported tons of bulk materials and the pile length decreases gradually because smaller portions of bulk materials are reclaimed during the storage time. By registering the pile locations, the releasing area can immediately be used for new incoming material.

For the modelling the process-interaction approach is used (Zeigler, 2000) and (Fishmann, 2001). In this approach the system is virtually broken down into relevant element classes each with their typical attributes, which results in an object oriented data structure of the system. For all active element classes process descriptions, which describe the functioning of this element as a function of time, have to be defined. The last step is to create all necessary elements according their classes and start the

processes of these elements. In the simulation model all active elements act parallel in time, synchronized by the sequencing mechanism of the simulation software (Ottjes and Lodewijks, 2004).

4.1 The simulation model

This paragraph explains the simulation model for an import terminal, which means that ships supply the bulk materials to the terminal. Piles are formed from these materials, and are reclaimed in smaller portions, represented with trains. The analogy for an export terminal is comparable, however, at export terminals trains import bulk materials in portions and large tonnages are exported by ships. A simplified representation of the simulation model is showed in Figure 5.

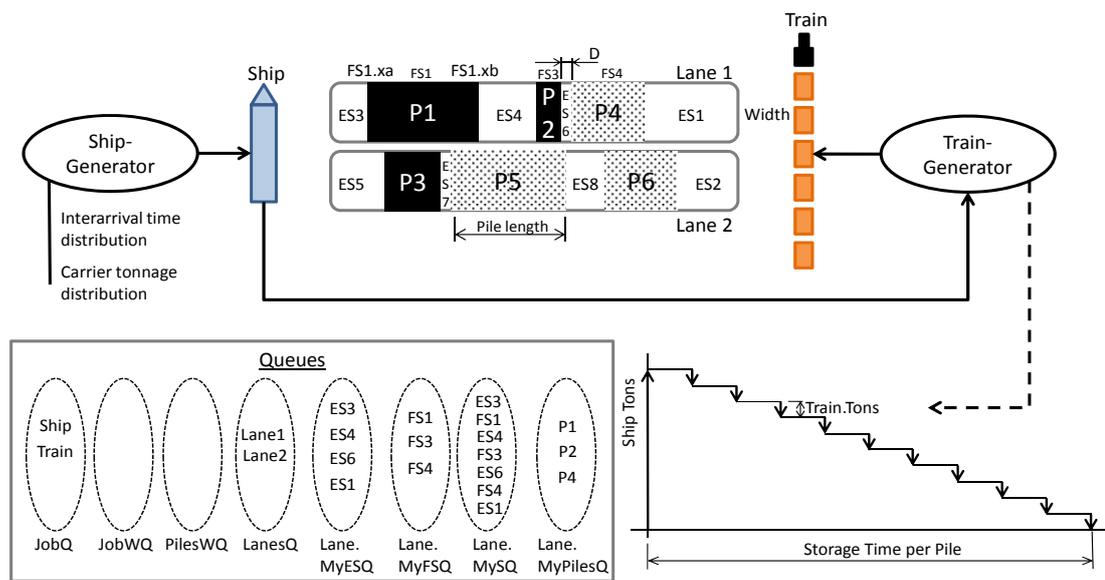


Figure 5: Simulation-based approach

Figure 5 shows the main classes of the simulation program (ShipGeneratorClass, TrainGeneratorClass, LaneClass, JobClass and StripClass). The ShipGenerator creates ships and each ship creates its own TrainGenerator, which generates trains. Both ships and trains belong to the JobClass. Attributes for JobClass and StripClass are mentioned in Table 1. The stockyard is represented by several lanes, which belong to the LaneClass (details for the LaneClass are listed in Table 4). The dimensions and locations for the piles at the stockyard lanes are registered with specific elements, which are called FullStrips and belong to the StripClass. At dry bulk terminals, a certain distance of at least two meters is used between two piles to prevent contamination; therefore in the simulation model the distance D is introduced. Strips which do not contain materials are called EmptyStrips and belong also to the StripClass. By registering and bookkeeping of the start positions (xa) and end positions (xb) of the FullStrips and EmptyStrips, the exact locations and tonnages of the bulk materials at the stockyard can be modeled.

The simulation model uses several queues, which are collections of elements. The JobQ (where ships and trains, which can be handled, are stored), the JobWQ (where waiting ships or trains are stored) and the PilesWQ (where waiting piles are stored) are general queues. Each lane contains specific queues and Figure 5 shows for a Lane

these queues filled with elements. An explanation for these queues can be found in Table 4.

From the main classes more details are presented below. Tables 1 to 6 show these element classes in the so called process description language. The common object oriented dot notation is used for qualifying methods and properties to the element classes. So for example Ship•Length means the length of the Ship and Ship=JobClass•Create causes creation of an instance of the JobClass and refer to it as Ship.

Table 1: JobClass and StripClass with their attributes

JobClass	StripClass
<u>Attributes</u>	<u>Attributes</u>
Tons : double	xa : double
Length : double	xb : double
Pile : PileClass	Tons : double
DetermineLength : Function	Length : double
	MyLane : LaneClass
	MyPile : PileClass

A ShipGenerator generates ships based on its interarrival time distribution and carrier tonnage distribution. The tons of each ship are stored separately in piles (represented in Figure 5 with P1 – P6) if there is area available on the stockyard lanes. Based on the ship tons the required pile length is calculated, more details to determine the pile dimensions are mentioned in paragraph 4.2. For each ship a pile is created. If there is area available somewhere at the stockyard, the ship is prepared for unloading by entering the JobQ else the ship and pile are putted in the JobWQ respectively the PilesWQ. The process ends with the creation of a TrainGenerator for each ship.

Table 2: ShipGeneratorClass with attributes and process

ShipGeneratorClass
<u>Attributes</u>
Ship : JobClass
MyTrainGen : TrainGeneratorClass
Process
Repeat
Advance Sample (InterArrivalTimeDist)
Ship=JobClass.Create
Ship.Pile=PileClass.Create
Ship.Length=JobClass.DetermineLength
Ship.Tons=Sample(CarrierTonnageDist)
If there is an EmptyStrip with length \geq MyJob.Length + D
then Ship.EnterQueue(JobQ)
else Ship.EnterQueue(JobWQ) and Ship.Pile.EnterQueue(PilesWQ)
MyTrainGen=TrainGeneratorClass.Create
MyTrainGen.MyShip=Ship

The TrainGenerator draws the pile's storage time out of a distribution. Based on the ship tons, the number of trains to export all material is determined using the maximum of tons per train. Furthermore, it is assumed that the interarrival time between two successive trains is constant (storage time per pile divided by the number of trains). The TrainGenerator creates Trains and defines the belonging attributes to the trains. If the material, which has to be loaded into the trains, is stored somewhere at the stockyard, the train is prepared for loading (in the simulation model the train enters the JobQ).

Table 3: TrainGeneratorClass with attributes and process

TrainGeneratorClass	
<u>Attributes</u>	
Train	: JobClass
MyShip	: JobClass
MaxTrainTons	: double //4,000 [t] is used
Process	
NrTrains=RoundUp(MyShip.Tons/MaxTrainTons)	
StorageTime= Sample(StorageTimeDist)/NrTrains	
Repeat for NrTrains	
Advance StorageTime	
Train=JobClass.Create	
Train.Tons=MyShip.Tons/NrTrains	
Train.Pile=MyShip.Pile	
Train.Length=MyShip.Length/NrTrains	
If Train.Pile IsInQueue(PilesWQ) then Train.EnterQueue(JobWQ)	
Else Train.EnterQueue(JobQ)	

If there is a Job in the JobQ, each Lane investigates one after the other if this Job can be handled with its specific function SelectJob (see for details Table 6). If this Job cannot be handled the result is nil and the Lane remains inactive. If the Job can be handled, this Job is selected and removed from the JobQ. If the selected job is a ship, the ship's pile is putted in MyPilesQ to assign this material to this lane. A FullStrip and new EmptyStrip are created. The EmptyStrip, with sufficient free length is searched (=MyES) and after finding the function Bookkeeping is activated. This function updates the dimensions of MyES and the new FullStrip and new EmptyStrip. Also the ship's tons are assigned to the FullStrip. At the end, the selected job is destroyed.

If the selected job is a train, the FullStrip is searched where the right material is stored (=MyFS) followed by an activation of the function Update. This function updates the dimensions and tons of MyFS and the corresponding EmptyStrip. If the remaining tons of the FullStrip equals zero, the FullStrip and its left EmptyStrip are destroyed after leaving the corresponding queues. Because free area arises the function CheckJobWQ is activated, if there are Jobs waiting before getting serviced in the JobWQ. Details of this function are listed in Table 5.

Table 4: Element LaneClass with attributes and process

LaneClass	
<u>Attributes</u>	
MyJob	: JobClass
MyPilesQ	: Queue
MyESQ	: Queue //EmptyStrips Queue
MyFSQ	: Queue //FullStrips Queue
MySQ	: Queue //AllStrips of this Lane Queue
SelectJob	: Function //check if NewJob can be handled by this Lane
CheckWQ	: Function //check if waiting jobs can be served
Bookkeeping	: Function //update dimensions and tons of FullStrip and EmptyStrips
Update	: Function //update dimensions (+tons) FullStrip and EmptyStrip
MyES	: StripClass //Existing EmptyStrip, already in MyESQ
Process	
Repeat	
While SelectJob=nil do standby	
MyJob.LeaveQueue(JobQ)	
If MyJob=Ship then	
Begin	
MyJob.Pile.EnterQueue(MyPilesQ)	
Create FullStrip and EmptyStrip	
Find MyES where MyES.Length >= MyJob.Length + D	
Bookkeeping	
Destroy MyJob	
End	
If MyJob = Train then	
Begin	
Find MyFS where MyFS.Pile = MyJob.Pile	
Update	
If MyFS.Tons = 0 then	
Begin	
LeaveQueues and Destroy of EmptyStrip and FullStrip	
If JobWQ.Length > 0 CheckJobWQ	
End	
End	
End	

Table 5: Function LaneClass.CheckWQ

LaneClass.CheckWQ	
<u>Attribute</u>	
MyJob	: JobClass
Process	
MyJob=JobWQ.FirstElement	
While MyJob <> nil do	
Begin	
If MyJob = Ship then	

```

Begin
  If there is an EmptyStrip with Length >= MyJob.Length + D then
    Begin
      MyJob.LeaveQueue(JobWQ) and MyJob.EnterQueue(JobQ)
      MyJob.Pile.LeaveQueue(PilesWQ)
    End
  End
End

If MyJob = Train and NOT MyJob.Pile.IsInQueue(PilesWQ) then
  Begin
    MyJob.LeaveQueue(JobWQ) and MyJob.EnterQueue(JobQ)
  End
  If MyJob.IsInQueue(JobWQ) and MyJob <> JobWQ.LastElement then
    MyJob=MyJob.Successor(JobWQ)
  End
End

```

Table 6: Function LaneClass.SelectJob

<u>LaneClass.SelectJob</u>
<u>Attributes</u> MyJob: JobClass MyES: StripClass
<u>Process</u> MyJob=JobQ.FirstElement While MyJob <> nil do Begin If MyJob = Ship then Begin If there is an EmptyStrip with Length >= MyJob.Length + D then Result=MyJob else Result=nil End End If MyJob = Train then Begin If MyJob.Pile.IsInQueue(MyPilesQ) then Result=MyJob else Result=nil End End End End

4.2 Determination of pile dimensions

Various types of stockpiles can be set up depending on the shape and size of the storage area. The basic stockpile type for open storage is the longitudinal stockpile. If the pile height is limited by the equipment (for example, most stacking machines are able to stack up to a maximum of 23 meters) the longitudinal stockpile gets a trapezoidal shape, see Figure 6. Equation 1 shows the mathematical relation to calculate the mass of that pile, which is derived from (UNCTAD, 1985).

$$m = \left[\frac{h}{h_{\max}} \left(2 - \frac{h}{h_{\max}} \right) \left(\frac{1}{4} w^2 \tan \alpha \right) \right] l \rho \quad (1)$$

(m : mass of the bulk materials [t], h : height of the stockpile [m], h_{\max} : maximum height the stockpile can attain [m] (see equation 2), w : width of the stockpile [m], α : angle of repose of the bulk material [$^{\circ}$] l : length of the stockpile [m] and ρ = bulk density of the bulk material [t/m^3]).

$$h_{\max} = \frac{1}{2} w \tan(\alpha) \quad (2)$$

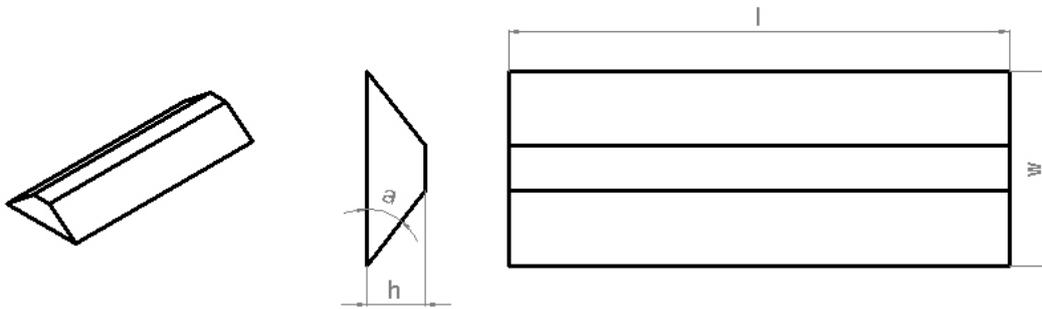


Figure 6: Trapezoidal stockpile

In reality the pile width varies between the 40 and 100 meter (Van Vianen et al., 2011), and the bulk density depends on the bulk material. In the simulation model is the stevedoring storage policy modeled, which means that the materials are stored separately to track the material's identity

However, in reality the pile length is limited. If a large volume of bulk materials must be stored in one pile, it requires a long, continuous, free strip at the stockyard area. Especially during daily operation at dry bulk terminals, it is quite uncommon that a large free strip of a couple of hundred meters exists. The ship has to wait or the terminal operator must relocate other bulk materials to realize the required free strip. That's why stevedores limit the tons per pile, and if more tons with the same material properties have to be stored, multiple piles are formed.

From a Dutch dry bulk terminal, the maximum tons per piles were examined during the year 2010. Figure 7 shows a histogram of this data for both coal and iron ore. The 95th percentile of the coal piles was 105 [kt] and for the iron ore piles 175 [kt].

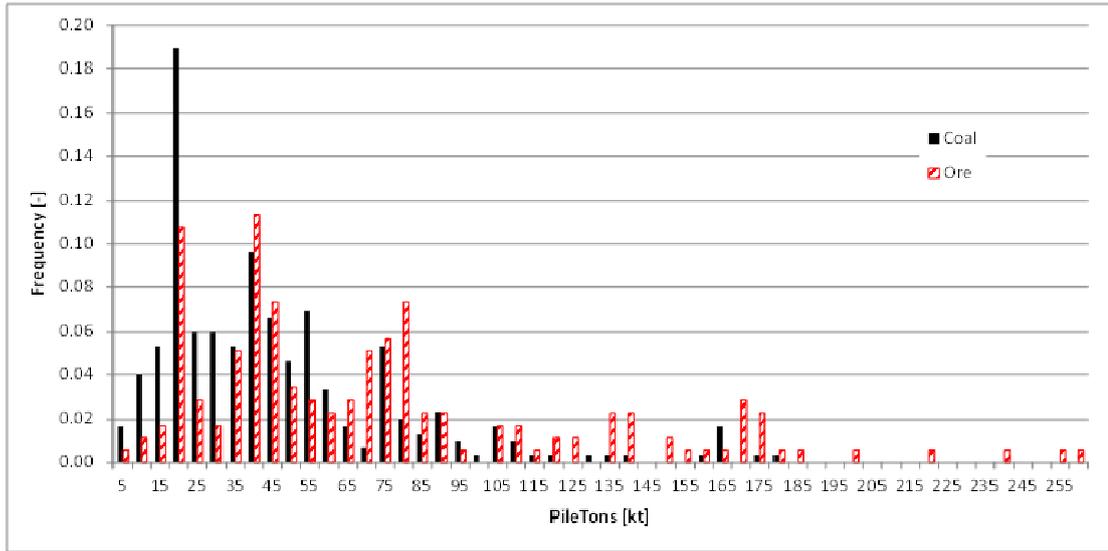


Figure 7: Maximum tons per pile for coal and iron ore

If a ship is generated in the simulation model with more than the allowed maximum tons per pile of 105 [kt] for coal and 175 [kt] for iron ore, partial jobs are generated instead of one job.

4.3 Method to determine the storage factor

The objective of the simulation model is to derive the storage factor as a function of several parameters. The storage factor is determined by measuring the maximum annual throughput of the terminal while no ships had to wait.

For determine this annual throughput, the total throughput is measured and divided by the simulation runtime. Simulation runs show that with a runtime of 20 years and using different seeds for the stochastic distributions (a seed is the starting point for series of random numbers), the variation of the measured total throughput was maximum $\pm 5\%$. This accuracy satisfies the objective of this research to determine the effects of the several parameters on the storage factor.

The storage factor is calculated with the following equation:

$$\frac{\left(\frac{\text{Total Throughput}}{T_{run}} \right)}{n_{lanes} l_{lanes} w_{lanes}} \quad (3)$$

(Total Throughput is the registered throughput of the seaside of the terminal [t], T_{run} is the simulation runtime [years], n_{lanes} is the total number of lanes [-], l_{lanes} is the lane length [m] and w_{lanes} is the lane width [m]. It is assumed that all lanes have the same length and width).

5 Results

Simulation runs are performed according the method described in the previous paragraph. Table 7 shows the used input parameters.

Table 7: Input parameters of the simulation runs

Parameter	Value	Unit	Parameter	Value	Unit
n_{lanes}	4	[-]	Carrier tonnage distribution	CTD* 1, 2 or 3 (see Table 8)	
l_{lanes}	1,000	[m]	Interarrival time distribution	NED, Erlang-2 or Deterministic	
w_{lanes}	60	[m]	Average storage time	1,000 – 3,000	[h]
h_{max}	18	[m]	Storage time distribution	Erlang-2	
α	38	[°]	Bulk material (bulk density)	Coal (0.8) and Iron Ore (2.6)	[t/m ³]
T_{run}	20	[years]	Max. tons per coal pile	105	[kt]
			Max. tons per iron ore pile	175	[kt]

* CTD = Carrier Tonnage Distribution

To investigate the consequence of the carrier tonnage distribution three table input distributions are researched, see Table 8. The first carrier tonnage distribution is an imaginary distribution and mainly based on smaller ships with an average carrier tonnage of 75 [kt], CTD2 represents the real carrier tonnage distribution of a Dutch import terminal (Van Vianen, et al., 2012) and CTD3 is also an imaginary distribution but then mainly based on bigger ships with an average carrier tonnage of 175 [kt].

Table 8: Carrier tonnage distributions

Tonnage min. [kt]	Tonnage max. [kt]	CTD 1	CTD 2	CTD 3
0	25	10 **	5	
25	50	10	19.4	
50	75	30	23.6	
75	100	30	10.1	20
100	150	20	12.3	20
150	200		25.5	30
200	300		4.1	30
Avg. tonnage [kt]		75	101	175

10** means that 10% of the ships are drawn from the table input distribution with a carrier tonnage between the 0 and 25 [kt].

To obtain results, four parameters have to be varied. Table 9 shows which parameters are varied for figures 8, 9 and 10.

Table 9: Varied parameters per figure

Figure	Interarrival time distribution	Carrier tonnage distribution	Bulk material	Average storage time [h]
8	Erlang-2	CTD2	Coal & Iron ore	1,000 – 3,000
9	NED, Erlang-2 and Deterministic	CTD2	Coal	1,000 – 3,000
10	Erlang-2	CTD1, CTD2 and CTD3	Coal	1,000 – 3,000

For each hundreds of the average storage time, the storage factor is determined and through these points a line have been drawn. Because of the already mentioned accuracy of $\pm 5\%$, these lines can show some irregularities.

Figure 8 shows the storage factors for coal and iron ore as function of the average storage time. If the average storage time of the piles increases, less tons of materials can be transhipped which results in smaller values for the storage factor. The difference between the storage factors for coal and iron ore can be explained by the difference in bulk density.

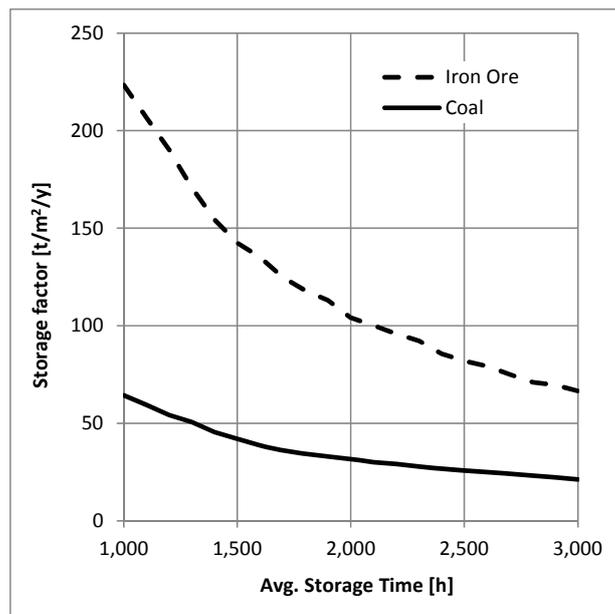
**Figure 8: Storage factor as function of bulk material and average storage time**

Figure 9 shows the storage factors for coal as function of the average storage time and interarrival time distribution type. Previous research showed that the interarrival time distribution depends on the terminal type, see paragraph 3.1. If the interarrival time is constant, the interarrival time distribution type is deterministic.

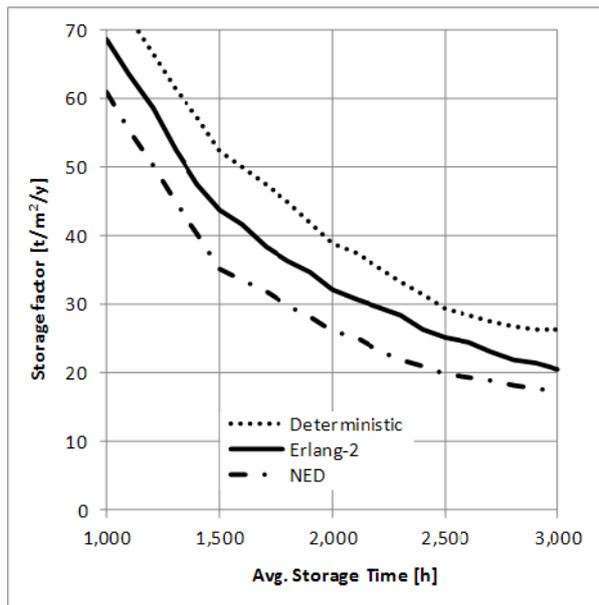


Figure 9: Storage factor as function of Interarrival distribution type and average storage time

From Figure 9 can be derived that the larger the variation in the ships interarrival times, the smaller the storage factor.

Figure 10 shows the storage factor for coal as function of the carrier tonnage distribution and the average storage time. The storage factors decrease when bigger ships are used to import the bulk materials. Especially, the difference between CTD1 and CTD2 is remarkable. If smaller portions of bulk materials are imported, it is easier to find available area to store these portions which will increase the terminal's annual throughput without waiting of ships.

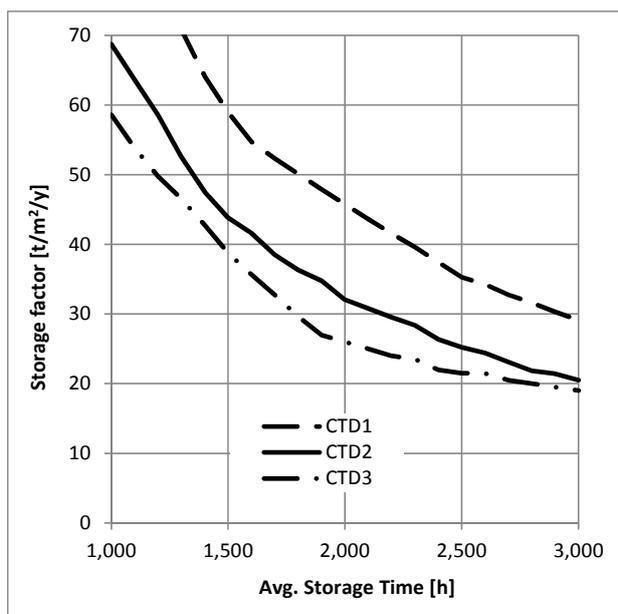


Figure 10: Storage factor as function of Carrier tonnage distribution and average storage time

6 Conclusions and future work

The storage factor is proposed to dimension the stockyard to realize a certain annual throughput. The storage factor [$t/m^2/y$], which is the ratio between the annual throughput [t/y] and the total storage area [m^2], relates to the interarrival times of the ships, ship sizes, average storage time, pile dimensions etc. In this paper the impact of these parameters on the storage factor was determined using discrete-event simulation. If the variation of the interarrival times increases or the average carrier tonnage increases, the storage factor decreases. Especially, the average storage time has a major impact on the storage factor, the larger the average storage time the smaller the storage factor.

Future research will focus on the determination of the storage factor as function of the parameters pile dimensions, storage policy and storage time distribution. With these data it is possible to determine the storage factor if all above mentioned parameters are known or assumed. This helps terminal designers to dimension the stockyard.

Acknowledgement

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