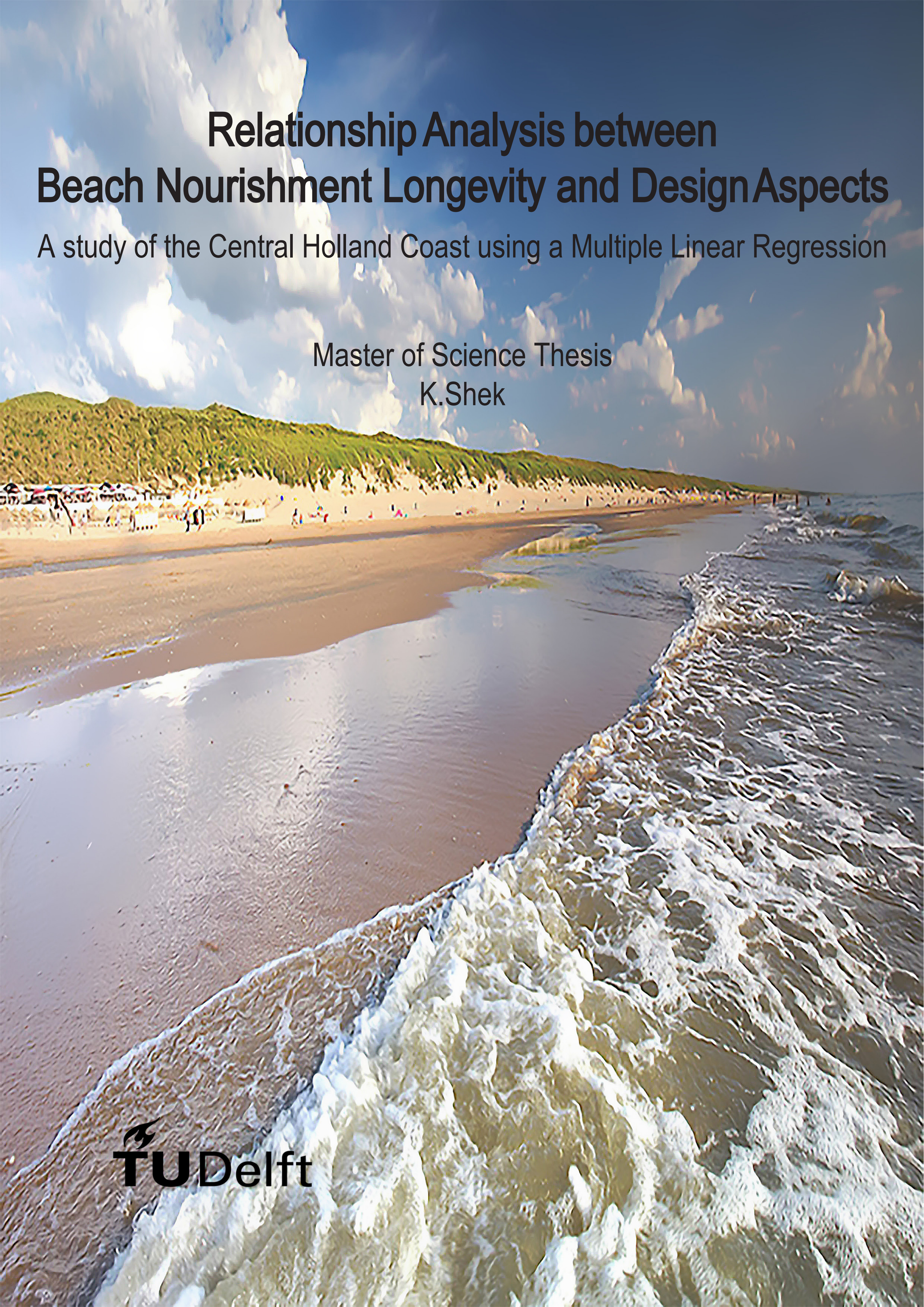

Relationship Analysis between Beach Nourishment Longevity and Design Aspects

A study of the Central Holland Coast using a Multiple Linear Regression

Master of Science Thesis
K.Shek

TUDelft

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A Study of the Central Holland Coast using a Multiple Linear Regression

Master of Science Thesis

by

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To obtain the degree of Master of Science in Civil Engineering

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Preface

Before you lies the Master of Science thesis 'Relationship Analysis between Beach Nourishment Longevity and Design Aspects'. It has been written to fulfil graduation requirements of the Master Hydraulic Engineering at the Delft University of Technology.

First of all, I would like to thank all the committee members for this great opportunity to work on this challenging topic. You gave me great advice and insights to complete this thesis successfully. Evelien, you were my direct supervisor from Rijkswaterstaat. I want to thank you for being my weekly supervisor. I am really grateful for your guidance and the valuable and constructive feedback during our meetings. I truly enjoyed our discussions and learned a lot from them. Next, I would like to thank Matthieu, Tosca and Martine from the Delft University of Technology for their enthusiasm and valuable feedback and advice.

Apart from my supervisors, I would also like to thank Rik from the University of Twente for the pleasant conversation about the similar research that we had conducted. I really appreciate your advice since it was very insightful. Further, I would like to acknowledge my colleague and fellow student Gerard for the fantastic talks and discussions about my topic. In addition, I would like to thank my colleagues from Rijkswaterstaat Petra, Rena, Emiel, and Gertjan for their help to obtain all the necessary information for this thesis. Next, I would like to thank all my friends from and outside the university for their positive distraction to rest my mind besides my research during COVID-19.

Finally, I would like to thank my family for their unconditional love and support. Without their belief, I would not be where I am today.

K. Shek
Delft, August 2021

Abstract

In the past decades, beach nourishments have been widely applied along the coast of the Netherlands. Different studies on beach nourishment have been conducted over the years. Most of these studies regard the design, execution method, morpho- and hydrodynamic behaviour, and ecological impact. However, the relationship between the design aspects and the longevity of beach nourishment is not well understood.

Here we show with the multiple linear regression (MLR) model that the design aspects volume per metre, height and length of beach nourishment are of interest to analyse the relationship with beach nourishment longevity in the central Holland coast. The storm variables were negligible according to the model since the regression coefficients are insignificant.

After numerous reruns of the MLR model, it was noticed that the regression coefficient of design volume per metre is fluctuating. This could indicate a positive, negative, or even no distinct correlation between the design volume per metre and longevity. Therefore, no clear conclusions could be drawn on the design of nourishment volume per metre in order to extend a longer beach nourishment longevity. According to the MLR model, the design length has a positive regression coefficient and design height a negative regression coefficient. These signs suggest that a lower design height elevation and longer design length will result in a longer beach nourishment longevity.

The computed beach nourishment longevities of the 7 locations (Julianadorp, Callantsoog, Bergen aan Zee, Egmond aan Zee, Bloemendaal aan Zee, Scheveningen, and Ter Heijde) along the central Holland coast showed that the average longevity of each location could not be interpreted with certainty. This outcome results from the given confidence level of the longevities and the number of beach nourishments used for the computation. Nevertheless, these computed longevities showed that a typical beach nourishment longevity along the central Holland coast is in the range of 3 and 3.5 years. Further, it was observed that computed beach nourishment longevities along the central Holland coast have increased between 1990 and 2020. The increase of beach nourishment longevity coincided with a policy shift in 1999 when shoreface nourishment became a common practice. Therefore, this data suggests that the presence of shoreface nourishment had a positive impact on the longevity of beach nourishments. Despite this result, no certain conclusion could be drawn as the positive contribution can also be caused by increasing nourishment volume through the years.

Overall, data-driven research forms the basis of this study and provides a first qualitative insight into the relationship between design aspects and beach nourishment longevity of the central Holland coast.

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List of Acronyms

BCL	Basal Coastline (Basiskustlijn).
EHS	Erosional Hot Spot (Erosie Hot Spot).
EIS	Environmental Impact Statement (Milieueffectrapport).
JARKUS	Annual Coastal Measurements (Jaarlijkse Kustmeting).
KNMI	Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut).
MCL	Momentary Coastline (Momentane Kustlijn).
MLR	Multiple Linear Regression (Meervoudige Lineaire Regressie).
MLW	Mean Low Water (Gemiddeld Laagwater).
NAP	Amsterdam Ordnance Datum (Normaal Amsterdams Peil).
NWP	National Water Plan (Nationaal Waterplan).
OLS	Ordinary Least Squares (Kleinste Kwadraten Methode).
RSP	Beach Pole (Rijksstrandpaal).
VIFs	Variance Inflation Factors (Variantie Inflatie Factor).

1 Introduction

1.1 Background

The sandy coastline of the Netherlands is not just an area where a line forms a boundary between land and sea. It is a unique and important region that protects millions of Dutch residents and their hinterland properties against flooding. Therefore, a coastal regression could have severe consequences for social, economic and geopolitical development. For this reason, coastal protection in the Netherlands is always relevant.

Coastal erosion along the Dutch coast had taken place for centuries. However, this natural phenomenon became more known in the last decades due to the accelerating sea-level rise by climate change (Stive, 2004). In 1990, the Dutch Ministry of Infrastructure and Water Management adopted a new coastal maintenance policy, where the focus lies on dynamic preservation (Ministerie van Vekeer en Waterstaat, 1990). This new policy intends to maintain the reference coastline that corresponds to the coastline position in 1990. The reference coastline is also called the basal coastline (BCL). To maintain the BCL, the momentary coastline (MCL) needs to be measured annually to determine the current coastline position relative to the BCL. When the MCL is expected to exceed the BCL position landward, sand nourishment is a preferred strategy to preserve the BCL position. The sand nourishment approach endeavours to maintain the sand balance of the coastal foundation and compensate for the structural erosion. There are different types of sand nourishment. One of the most common types is beach nourishment, where large volumes of sediment are deposited in the beach area. Although this method works well to ensure the BCL preservation, the behaviour and effectiveness of beach nourishment in relation to design aspects are still not well understood.

In the last decades, data-driven research has been performed more by coastal engineers because of the abundant monitoring along the Holland coast for many years. All these researches have resulted in considerable extensive data for large-scale data analysis. The Directorate-General for Public Works and Water Management (Rijkswaterstaat), who is responsible for the management and maintenance of the entire Dutch coast, has collected a unique dataset of annual topographic profiles and the characteristics of the performed nourishments since the 1960s. This comprehensive measured data has various purposes. The practical purpose is to obtain information about the coastline development and erosion rate for coastal management. The valuable data can also be used for the scientific purpose to gain more knowledge into the unknowns concerning the coast and nourishments. The insight obtained from the data analysis can be extremely informative for coastal engineers to enhance future coastal maintenance decisions.

1.2 Problem Description

Beach nourishment is a method that has been widely applied in the Netherlands and the rest of the world (Hanson et al., 2002). In the last decades, different studies about beach nourishment have been conducted. Most of the studies about beach nourishment regard the (i) design [e.g., Verhagen (1992), Pilarczyk (1988), Dean and Yoo (1992)], (ii) execution method [e.g., Dean (2003),d'Angremond (1992), Van Oorschot and Van Raalte (1991)], (iii) morpho- and hydrodynamic behaviour [e.g., Tonnon et al. (2018), Dette et al. (2002), Work and Rogers (1997)] and (iv) ecological impact [e.g., Adriaanse and Coosen (1991), Arens et al. (2012), Grain et al. (1995)]. Even though beach nourishments have been studied globally, the relation between design aspects and nourishment longevity is not well understood.

In 1992, Verhagen has conducted a study about the principle of beach nourishment design. Verhagen discussed briefly how design aspects might affect beach nourishment effectiveness. However, everything he concluded in his study about design aspects was based on subjective experiences. In addition, Verhagen stated that detailed research about this topic including data was impossible. The conceivable reason for the statement is a lack of the right data in the past to carry out this kind of specific study.

In 2018, a study was carried out by Gijsman et al. to classify the influence of individual design parameters on the nourishment lifetime in a specific study area (Sylt, Germany). They found out that a higher beach nourishment elevation, larger nourishment volume and longer nourishment length will result in a longer nourishment lifetime. Additionally, they have concluded that the lifetime of beach nourishments seems to decrease in the alongshore downstream direction. Despite the results, there are some limitations and uncertainties. For instance, this analysis only clarifies the influence of the design parameters on the beach nourishment lifetime in Sylt. Therefore, these results cannot be implemented in other coastal areas.

Based on the available research, it can be concluded that there are still unresolved questions about the relationship between design aspects and nourishment longevity.

1.3 Research Objective

This study aims to examine beach longevity based on annual cross-shore profile data of the central Holland coast (beach-dune coast of central Holland) with an appropriate statistical model. A statistical model is applied to analyse the relationship between design aspects and nourishment longevities with the approximately 50 years of collected nourishment and cross-shore profile data of Rijkswaterstaat. By doing so, an understanding can be developed of the extent to which design aspects affect the longevity of beach nourishment. This allows a better impression of beach nourishment behaviour, which could help coastal engineers or authorities improve beach nourishment design decision-making.

1.4 Research Questions

The problem description and research objective lead to the following main and sub research questions.

1.4.1 Main Question

The main question of this research is formulated as follows:

> ***Which design aspects are primarily affecting the beach nourishment longevity along the central Holland coast?***

1.4.2 Sub Questions

The following sub-questions have been formulated to answer the main question:

1. ***What are the longevities of beach nourishments along the central Holland coast?***
2. ***To what extent has the longevity of beach nourishments changed over time?***
3. ***To what extent do nourishment design aspects (volume per metre, length and height) have an influence on the longevity of beach nourishments?***
4. ***To what extent have beach nourishments effect on longevity that are applied shortly before a storm?***

2 Literature Review

It is crucial to evaluate the fundamentals of beach nourishment first, which is essential to understand the beach evolution (or alteration) upon beach nourishment. Afterwards, different aspects of beach nourishment will be considered, such as design aspects, coastal processes, and nourishment strategies. A better understanding of these subjects is of great importance since it provides insight into beach nourishment's behaviour and effectiveness. Therefore, the main aspects essential for this research will be discussed briefly in this chapter with the corresponding literature.

2.1 Beach Nourishment

Artificial beach nourishment is widely practised in the world. In the Netherlands, beach nourishment can be considered adequate for coastline preservation based on decades of experience. Beach nourishment is known for placing a large amount of sediment on the beach area. According to Verhagen (1992), the purpose is to restore an eroding coastline, prevent flooding or maintain a wide recreational beach. Beach nourishments are often performed in erosion-prone areas, also called erosional hot spots (EHS). These areas have a higher erosion rate as compared to the adjacent beaches (Kraus and Galgano, 2001). Due to the natural loss of sediment along the coast, the beach fill is only appropriate for a limited time. According to Staudt et al. (2021), in general, beach nourishments along the Dutch coast have a longevity of approximately 4-5 years. Therefore, beach nourishments should be repeated regularly. Van Oorschot and Van Raalte (1991) have reported that there are several methods for nourishing the beach area (e.g., barges, pipeline, and rainbowing). d'Angremond (1992) has addressed that the choice of method depends on the objective, ecology, location, and economic point of view.

The main characteristic of beach nourishments is the immediately noticeable effect. The coastline moves directly in a seaward direction due to the implementation. However, this coastline will move landward over time due to the natural erosion and forced erosion processes created by the nourishment itself. The latter is described by Verhagen (1992). This phenomenon is caused by an unstable and out of equilibrium beach profile. The nourished sediment tends to erode rapidly in the months after nourishment to bring the profile back in equilibrium. The sediment transport and morphology in the nearshore change three-dimensional. Therefore, sediment diffusivity will occur in the cross-shore and longshore direction after the performance of beach nourishment. Benedet et al. (2007) have addressed that the change in coastline orientation induced by beach nourishment will increase the local current velocity and therefore erode the nourished beach. In addition, Dean (2003) has described that the erosion rate after beach nourishment follows an exponential decay law.

2.2 Design Aspects

According to Hanson et al. (2002), the Netherlands has a more consistent design compared to other European countries. The design of beach nourishment along the coast is essential. It is expected that each design aspect has its contribution to the beach nourishment performance. In the Netherlands, the following design aspects are considered: (i) sediment characteristic, (ii) nourishment height, (iii) nourishment slope, (iv) nourishment volume, and (v) nourishment length. As mentioned in the previous section, the beach profile adaptation due to nourishment can change the importance of some coastal processes over others. Consequently, it can cause an adverse effect on beach nourishment performance. Therefore, it is important to understand how the decision making of each design aspect could positively or negatively influence the beach fill and the surrounding area. The considered design aspects of beach nourishment are illustrated in Figure 2.1, except for the sediment characteristic.

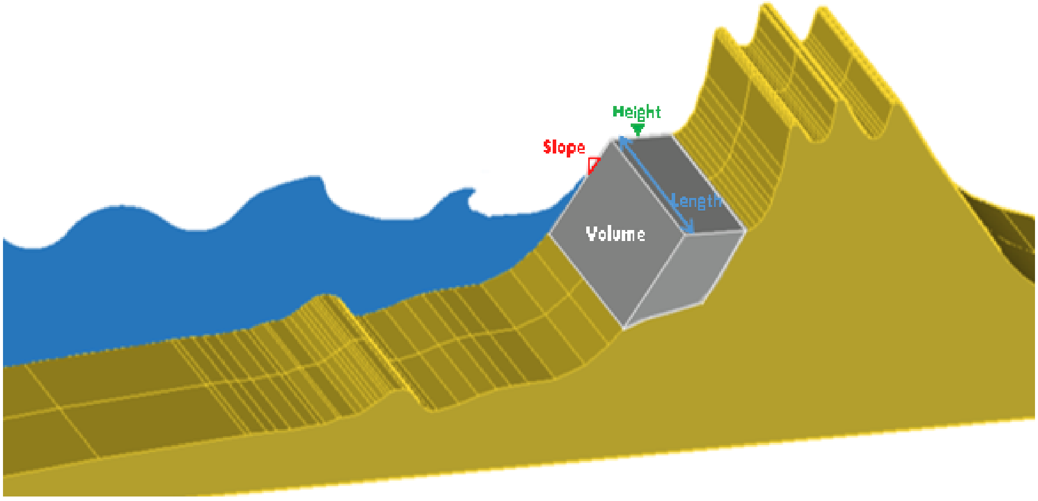


Figure 2.1: A sketch of the beach nourishment's design aspects.

Sediment Characteristic

The type of nourished sediment is an important design aspect. The relative sediment characteristics decide how the beach will shape after beach nourishment is carried out. Before nourishing a beach, suitable sediment must be obtained from one or more borrow areas. The borrow areas are located offshore (marine source) or onshore (land-based). In the Netherlands, there are specific offshore borrow areas selected in the North Sea. According to van Duin et al. (2017), the specific locations of the borrow areas are designated in the Environmental Impact Statement (EIS). This report assesses the possible alternatives and consequences prior to dredging actions in the North Sea.

Dean (2003) has addressed that it is preferable to borrow a similar grain size as the sediment present in the original beach profile since a significant difference in the sediment can change the slope and other coastal features and alter the currents, waves, and sediment transport. However, this is hardly feasible in practice. The grain size is often finer or coarser than the native sediment. For constructing beach nourishment, coarser sediment is more often applied to diminish sediment loss. According to Dean (2003), coarse grains will yield a smaller longshore transport rate compared to fine grains. Overall, this leads to less erosion of the nourished sediment and therefore a longer nourishment longevity. Consequently, if native sediment is not available for nourishment, the use of coarse grains extracted from borrow areas is of more interest to sustain longer nourishment longevity.

Nourishment Height

Dean (2003) has reported that a higher nourishment elevation is more effective against wave impacts by severe storms. However, this will form an abrupt elevation difference on the beach, which is called a scarp. According to van Bemmelen et al. (2020), beach scarps are likely formed on nourished sites with high platform elevation and is often associated with eroding (nourished) coastlines. This phenomenon could be dangerous for recreational swimmers during high tides. Therefore, it is believed that maintaining the berm height close to the natural beach level is a great way to find a balance between design objective and safety (Dean, 2003).

Nourishment Slope

Pilarczyk (1988) has reported that nature tends to flatten the slope into the range of roughly 1:70 to 1:30 when a beach slope is out of equilibrium. Dette and Raudkivi (1995) have concluded that a flat seaward slope cause a reduction in sediment losses. Apparently, when waves can freely run up and down the slope, the losses are minimised due to more wave energy dissipation. Consequently, the beach nourishment slope is constructed frequently at a natural angle to minimise the impact on the replenished sediment.

Nourishment Volume

According to Verhagen (1992), the amount of nourishment volume is determined by the annual average erosion rate derived from the regression over the previous 10 years and the expected design lifetime. Santinelli (2010) has conducted studies about the effect of nourishment volumes on the morphological evolution along the Holland coast. He concluded that the trend of natural erosion has increased since applying nourishment. To ensure the balance of the coastal foundation, the design of nourishment volume is a significant aspect to counteract sea-level rise and natural erosion.

Nourishment Length

The design length of beach nourishment depends on where the beach needs to be protected against erosion. Verhagen (1992) has stated that the beach nourishment length is usually 20 - 40 times the width of the nourishment. Van Rijn (2011) has reported that the length of beach nourishment needs to be at least 3 kilometres to mitigate the erosion at both alongshore ends due to the dispersion effect under normal wave attack. Drønen et al. (2017) have conducted a partial study about how beach nourishment length will affect the relative nourishment volume decay over the years by using a morphological 2DH model. Their results show that a longer beach nourishment length results in a slower relative volume decay.

2.3 Coastal Processes

As beach nourishment is performed, the nourished sediment will be redistributed in the cross-shore and longshore directions. Bosboom and Stive (2015) have stated that seasonal changes have a significant effect on the cross-shore beach profile. For seasonal variation, a distinction between summer and winter conditions is made. A summer condition provides a steeper and higher beach profile, while a winter condition represents a lower and more gentle beach profile. These seasonal cross-shore profile characteristics are mainly caused by the associated wave conditions. During summer, the wave conditions are mild. In response to these conditions, the sediment on the beach moves onshore, which results in a summer beach profile. Conversely, the generated waves during winter storm conditions result in sediment moving offshore and reverses the profile into a winter beach profile.

The seasonal variation from summer to winter beach profile often leads to the anticipation by public observers that beach nourishment is not effective since the wide beaches have dissipated. However, this conclusion is incorrect. d'Angremond (1992) has addressed that the eroded sediment is not completely lost but is redistributed underwater under a natural slope. After the storm, the mild wave condition redistributes the sediment above the low waterline.

In the shoreface area of the central Holland coast, sandbars are present. The movement of the sandbars in the cross-shore profile can also be related to seasonality. In the winter, one or more sandbars generally move offshore and move little onshore during summer. The net offshore displacement shows a cyclic behaviour. Giardino et al. (2012) have reported that the cyclic behaviour varies between 4-5 years, and at some locations it can even reach 15 years. According to Van Rijn (2011), the location of sandbars plays an important role in accretion or erosion of the natural beach and beach fill. Based on field experience, van Rijn (2003) has reported that the beach volume per unit width increases or decreases with the increasing or decreasing crest elevation of the sandbar. This coastal behaviour can be explained since the sandbar's location determines the magnitude of energy dissipation due to wave breaking. As a result, the change in wave energy due to the sandbar will affect the morphological response of the beach (Bosboom and Stive, 2015).

Seymour (2005) has addressed that the action of oblique incident waves and tides cause longshore currents that result in longshore sediment transport. This transport distributes the replenished sediment in the longshore direction. The change in coastline shape depends on the rate of longshore transport. Human interventions along the coast can modify the longshore transport since coastal structures (e.g., jetties, groynes, and shore-normal breakwaters) tend to block the longshore transport. Consequently, the coastline experiences accretion on the updrift and structural erosion on the downdrift side of the structure. The downdrift erosion can be mitigated with beach nourishment.

In conclusion, the coast is constantly changing in both cross-shore and longshore directions. The difference in the effect on the replenished sediment can be attributed to natural sediment erosion. The erosion in the cross-shore is considered temporarily, whereas in the longshore profile, the erosion is considered permanent.

2.4 Nourishment Strategy

The beach nourishment performance is partially dependent on the design. The effect of renourishment also needs to be taken into consideration. In areas where nourishment is required, multiple nourishments are generally performed. Dean (2003) has examined multiple nourishments and has shown that the time interval between successive renourishments will enhance. This outcome explains that each performed nourishment is counted as an additional nourishment project for all previous nourishments. Over the decades, multiple beach nourishment has been a preferred strategy along the Holland coast to protect the shore. Around the mid-nineties, shoreface nourishments became part of this strategy as well.

Van Duin et al. (2004) have reported that shoreface nourishments are placed in the shoreface area and act as a feeder berm to widen the beaches. It is observed that shoreface nourishment can positively affect beach zone to a certain extent. However, these effects are not immediately visible and are a more long term maintenance strategy. Shoreface nourishment can be combined with beach nourishment. According to Van Duin et al. (2004), shoreface nourishment was introduced in Egmond aan Zee to extend the lifetime of beach nourishment. Different studies have been conducted about the contribution of shoreface nourishment to the beach width [e.g., Van Duin et al. (2004), Walstra et al. (2004), Grunnet and Ruessink (2005), Ojeda et al. (2008)]. However, the conclusions of these studies vary.

2.5 Conclusion

Overall, one can conclude that the development of the beach after beach nourishment can not be assessed by just one aspect. In fact, various aspects need to be taken into consideration in order to provide considerable insights into beach nourishment performance. Thus, the importance of assessing multiple aspects can not be emphasised enough.

3 Study Area

In this chapter, the study area will be discussed. The focus lies on indicating the performed nourishments and classifying the coastal characteristics along the coast. This is necessary to understand which locations are of interest, what the distinctions are between these locations and how the nourishment scheme has changed. Altogether, it provides a good impression of the study area.

3.1 Central Holland Coast

The study focuses on the central Holland coast of the Netherlands. This region can be divided into the coastal sections (coastal section number): Noord-Holland (7), Rijnland (8) and Delfland (9). The central Holland coast is characterised as a sandy, micro-tidal, wave-dominated coast and has a length of around 117 kilometres. The coastal boundaries of this region are situated at Marsdiep (tidal inlet connecting the North and Wadden Sea) and Nieuwe Waterweg (artificial mouth connecting Rhine and Meuse river with the North Sea). The plan view of the central Holland coast is presented in Figure 3.1

Figure 3.1: An overview map of the central Holland coast with the coastal sections (Noord-Holland, Rijnland, and Delfland) and the corresponding longshore transports (white arrows). Be aware that the jetties are not drawn to scale. Source of longshore transport: Van Rijn (1995).

In the nearshore area of the central Holland coast, migrating sandbars are present. The sandbars are situated alongshore and generally move in a cyclic behaviour. The initial sandbars are formed in the inter-tidal zone and move in the offshore direction to the zone of decay (Spanhoff and van de Graaff, 2007). The decay of the outer bar initiates the next shoreward bar (Walstra, 2016). Along the central Holland coast, the number of sandbars and cycle time varies per coastal section. The cyclic behaviour varies between 4 - 5 years, and at some locations it can even reach 15 years (Giardino et al., 2012).

In addition, there are several coastal structures along this coast. These man-made structures have a significant influence on coastal development (Wijnberg, 2002). The most dominant structures are the long harbour jetties of Hoek van Holland (Delfland) and IJmuiden (Rijnland).

The central Holland coast is known for its erosive shoreline. According to the sand-budget model of Van Rijn (1995), the netto alongshore sediment transport is mainly directed to the north. Only at the north of IJmuiden, it is noticed that the longshore transport is directed to the south. The sand volume of longshore transport varies in the range of approximately 175.000 and 520.000 m³/year.

3.2 Locations of Interest

The cross-shore profiles along the central Holland coast are measured annually at every transect. These transects are associated with the fixed beach poles (RSP) at around every 250 metres along the coast. The central Holland coast has in total 501 transects.

In order to find the locations of interest, it is of importance to know in which transects beach nourishments have been performed. The interval of these transects will indicate the location. In Table 3.1 the interesting locations and their corresponding transect intervals along the central Holland coast are summarised.

Table 3.1: A list of potential locations with the corresponding transect intervals for the coastal sections (Noord-Holland, Rijnland, and Delfland) along the central Holland coast.

No.	**Coastal Sections**	**Locations**	**Transect Interval**
1	Noord-Holland	Julianadorp	170 - 528
2		Callantsoog	1137 - 1340
3		Bergen aan Zee	3175 - 3275
4		Egmond aan Zee	3725 - 3800
5	Rijnland	Bloemendaal	6175 - 6300
6		Zandvoort	6650 - 6700
7		Noordwijk	8100 - 8200
8	Delfland	Scheveningen	9950 - 10075
9		Ter Heijde	11034 - 11244

According to Giardino et al., the coastal features (e.g., cross-shore profile, number of nearshore bars, cycle time of nearshore bars, and littoral transport) vary in general along the coastline. Therefore, it is relevant to know how the coastal characteristics differ between locations to understand the study area. In the following section, different coastal characteristics are identified based on the study of the central Holland coast by Giardino et al. (2012, 2013) and the cross-shore profiles from the JARKUS survey.

In Figure 3.2 the positions of the 9 potential locations are illustrated in the coastal sections (Noord-Holland, Rijnland, and Delfland). Along the coastal sections, ascending RSP numbers are shown from north to south to indicate where the transects are located in the coastal sections. For each potential location, a brief characteristic summary is given and will be discussed in more detail in the following sections.

Julianadorp (1):
- Shoreline retreat
- Presence of one nearshore bar
- No net on- or offshore bar cycle
- Littoral transport directed to the north

Callantsoog (2):
- Shoreline retreat
- Presence of one nearshore bar
- No net on- or offshore bar cycle
- Littoral transport directed to the north

Bergen aan Zee (3) & Egmondl aan Zee (4):
- Shoreline retreat
- Presence of multiple nearshore bars (1-2 bars)
- Cycle time of bars is aproximately 15 years
- Littoral transport directed to the south

Bloemendaal (5) & Zandvoort (6):
- Shoreline retreat
- Presence of multiple nearshore bars (2-3 bars)
- Cycle time of bars is approximately 4 years
- Littoral transport directed to the north

Noordwijk (7):
- Shoreline retreat
- Presence of multiple nearshore bars (2-3 bars)
- Cycle time of bars is approximately 4 years
- Littoral transport directed to the north

Scheveningen (8) & Ter Heijde (9):
- Shoreline retreat
- Presence of multiple nearshore bars (1-2 bars)
- Cycle time of bars is approximately 4 years
- Littoral transport directed to the north

Figure 3.2: Overview map of the different coastal characteristics per potential location along the central Holland coast. The longshore transports are indicated with white arrows. Be aware that the jetties are not drawn to scale. Source of longshore transport: Van Rijn (1995).

3.2.1 Noord-Holland (RSP 20-5500)

Along the coastline of Noord-Holland, the coastal characteristics differ among the potential research locations. At the location of Julianadorp (RSP 170 - 528), the coast is known for its steep eroding profile with the presence of a nearshore bar and longshore transport directed to the north. The tide mainly determines the morphology as this coastline is located close to the tidal channel of Marsdiep. The coastline at Callantsoog (RSP 1137-1340) is similar to the coastline at Julianadorp but with a flatter profile. However, it is observed that the coastal profile tends to steepen over time.

More to the south of Callantsoog, the locations Bergen aan Zee (RSP 3175-3275) and Egmond aan Zee (RSP 3725-3875) are situated. These locations are much unalike compared to the northern coast of Noord-Holland. The coastline position is fluctuating slowly and moving onshore and offshore over a time period of approximately 15 years. This time period is similar to the time cycle for the multiple sandbars (1-2 bars). Further, it is noticed that only in this part of the central Holland coast, the longshore transport moves to the south of the harbour jetty in IJmuiden. At the updrift side of this jetty, coastal accretion occurs.

Figure 3.3 presents the cross-shore profiles of the potential locations along the coastal section of Noord-Holland. It can be observed in the figure that the cross-shore profiles at every location are relatively comparable except for the steep cross-shore profile of Julianadorp. In the cross-shore profiles, it is observed that the bed elevation is higher than the average bed profile at some cross-shore distance. This phenomenon is a sandbar feature. As can be seen in the figure, there are 1 or 2 sandbars at almost each location.

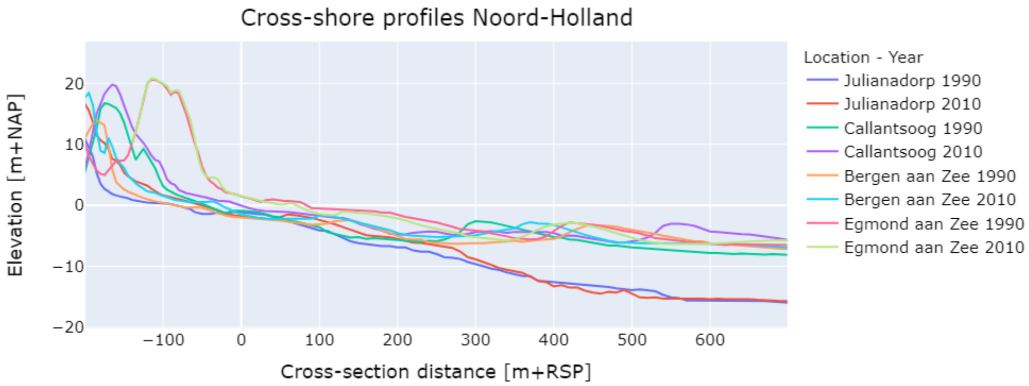


Figure 3.3: The average cross-shore profiles (1990 and 2010) of coastal section Noord-Holland with the potential research locations (Julianadorp, Callantsoog, Bergen aan Zee, and Egmond aan Zee).

3.2.2 Rijnland (RSP 5625-9725)

In the coastal section of Rijnland, there are three locations of interest. The first two locations, Bloemendaal (RSP 6175-6300) and Zandvoort (RSP 6650-6700) are situated close to the downdrift side of the harbour jetty IJmuiden. The third location, Noordwijk (RSP 8100-8200), is located further south of Zandvoort. All three locations experience coastline retreat. Multiple sandbars (2-3 bars) are present at these locations with a cycle time of approximately 4 years. The coastline at the downdrift side of the IJmuiden jetty is experiencing accretion. This accretion is due to the coastal structure that stops the longshore transport directed to the north.

Figure 3.4 shows the cross-shore profiles of the potential locations along the coastal section of Rijnland. In general, it can be observed that the cross-shore profiles are relatively similar. At every cross-shore profile, multiple sandbars are present. In the figure, it is also depicted that the dunes of Noordwijk have relatively low dunes compared to the locations Bloemendaal aan Zee and Zandvoort. The reason for an elevation difference is due to the dike-in-dune design. This multi-functional design withstands wave attack without having a high dune instead.

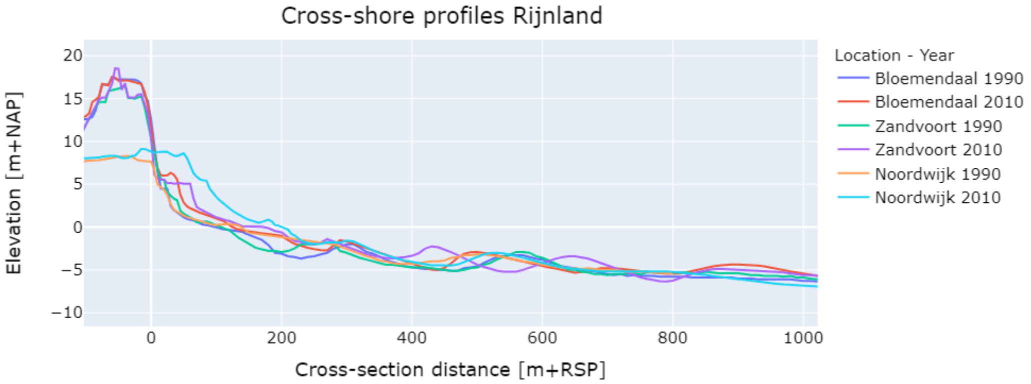


Figure 3.4: The average cross-shore profiles (1990 and 2010) of coastal section Rijnland with the potential research locations (Bloemendaal, Zandvoort, and Noordwijk).

3.2.3 Delfland (RSP 9740-11850)

The two locations in Delfland are Scheveningen (RSP 9950-10075) and Ter Heijde (RSP 11304-11244). Both locations are experiencing coastline retreat and have multiple sandbars (1-2 bars) with a cycle time of approximately 4 years. The longshore transport in this coastal section is directed to the north.

Figure 3.5 shows the cross-shore profiles of the potential locations along the coastal section of Delfland. In general, it can be observed that the cross-shore profiles in Scheveningen and Ter Heijde have changed through time, but the lower shoreface profiles are quite similar. An explanation for this observation is the implementation of large dune and beach nourishments in 2009 (Kuijper et al., 2016). The dune and beach nourishments resulted in the increase in steepness of both locations' profiles. Further, it is noticed from the four cross-shore profiles that only the cross-shore profile of Ter Heijde 2010 presents a sandbar.

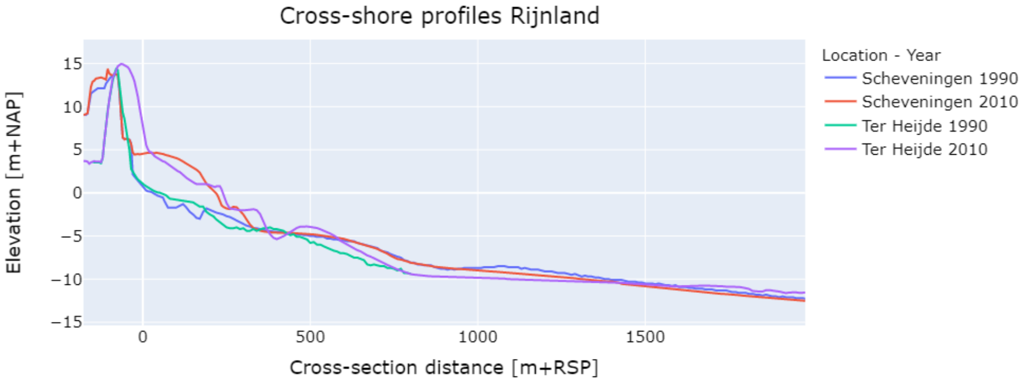


Figure 3.5: The average cross-shore profiles (1990 and 2010) of coastal section Delfland with the potential research locations (Scheveningen and Ter Heijde).

3.3 Nourishment Scheme

Since the implementation of the ‘Dynamic Preservation Policy’ in 1990, artificial sand nourishment became the preferred method to maintain the coastline in its 1990 position. The volume nourishment scheme for the whole Dutch coast has increased through the years to realise this objective. The yearly average nourishment volume increased from 3 million to 6 million m³/year in 1990 and approximately 12 million m³/year in 2001.

The area graphs of three coastal sections along the Holland coast are presented in Figure 3.6. The area graphs show a general overview of the total nourishment volume per year of different nourishment types at each coastal section. In general, it is observed for all the three coastal sections that the nourishment strategy between 1965 and 1990 consisted mainly of beach nourishments. Although, shoreface nourishments became a significant part of the nourishment strategy from 2000 onward. As illustrated in Figure 3.6, the applied shoreface nourishment volumes are approximately twice as large as the beach nourishment volumes.

It can be seen in the area graph of coastal section Noord-Holland that other types of nourishments (e.g., dune and channel wall) are also included in the nourishment strategy. For the coastal sections of Rijnland and Delfland, other types of nourishment do not play a significant role. Another remarkable result can be observed in the coastal section of Delfland. In the area graph, two-volume spikes of beach nourishments are visible, which are the result of the two mega nourishment projects (Dixhoorndriehoek in 1971 and Sand Engine in 2011) (Tonnon and Nederhoff, 2016). The nourishment volumes are equivalent to 19 million and 21.5 million cubic metres. The mega nourishment volumes are one order of magnitude larger compared to the other performed nourishments.

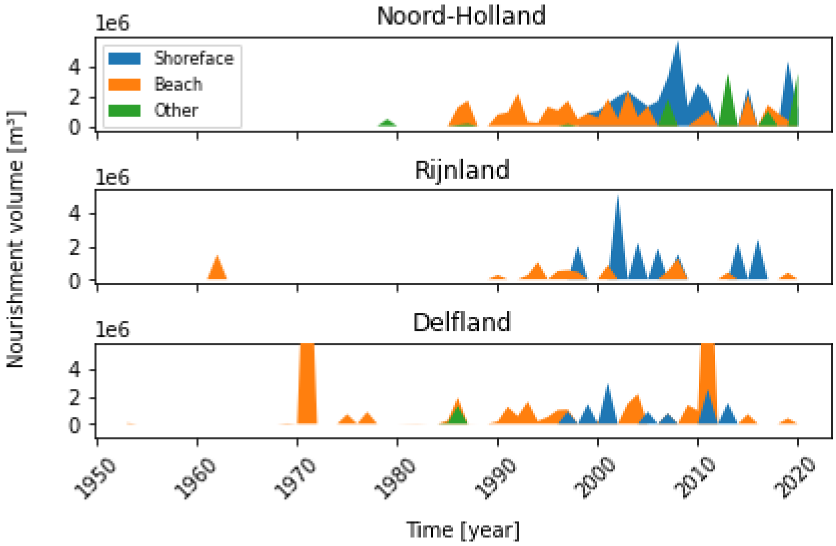


Figure 3.6: An overview of different types of nourishment (beach, shoreface and other) performed in the three coastal sections (Noord-Holland, Rijnland, and Delfland) between 1950 and 2020.

Figure 3.7 presents scatter graphs of the performed beach and shoreface nourishments in the three coastal sections between 1985-2020. Before interpreting the results, it should be mentioned that the beach nourishment of 2011 (Sand Engine) in Delfland is omitted. By doing so, the scatter graph of Delfland becomes more evident compared to other coastal sections.

It is apparent in Figure 3.7 that beach and shoreface nourishments are mostly performed in coastal section Noord-Holland. Additionally, what stands out in Figure 3.7 is the number and frequency of the beach and shoreface nourishments. In general, the number and frequency have decreased through the years for all coastal sections.

The average beach and shoreface nourishment volumes are computed for three-time intervals (1991-2000, 2001-2010, 2011-2020), see Table 3.2. It can be noticed that the average volumes of both beach and shoreface nourishment increased when comparing the second time interval with the first time interval. When comparing the third time interval with the second time interval, it can be seen that the average beach nourishment volume has increased for each coastal section, except for the coastal section Rijnland. In Delfland, the volume has increased significantly. This is a result of the Sand Engine. For the average shoreface nourishment volume, it is observed that the average volume has decreased in general. Only for the coastal section Rijnland, an increase is noticed.

All in all, the findings suggest that the nourishment strategy has changed considerably over time in the central Holland coast. The changes are observed in the number, frequency, and volume of beach and shoreface nourishments.

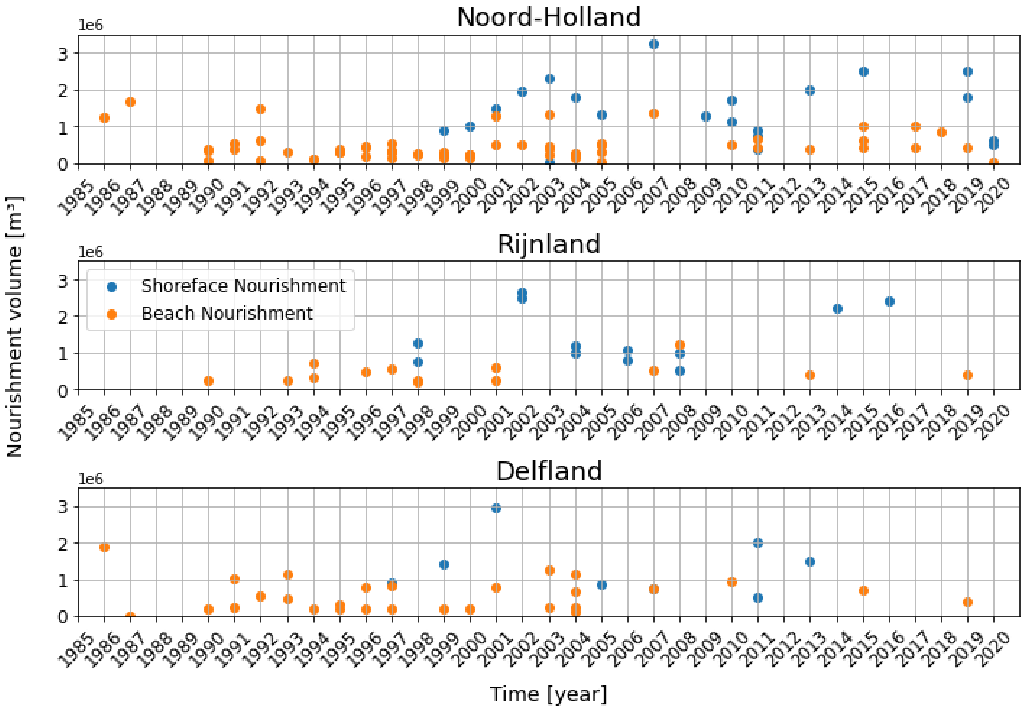


Figure 3.7: An overview of the performed beach and shoreface nourishments in the three coastal sections (Noord-Holland, Rijnland, and Delfland) between 1985 and 2020.

Table 3.2: The average beach and shoreface nourishment volumes of three time intervals of coastal sections (Noord-Holland, Rijnland, and Delfland).

Coastal Section	Year	Beach Nourishment Volume [m³]	Shoreface Nourishment Volume [m³]
Noord-Holland	1991 - 2000	325065	937050
	2001 - 2010	525870	1969823
	2011 - 2020	555715	1321115

Coastal Section	Year	Beach Nourishment Volume [m³]	Shoreface Nourishment Volume [m³]
Rijnland	1991 - 2000	398343	1009683
	2001 - 2010	649438	1340777
	2011 - 2020	405000	2300000

Coastal Section	Year	Beach Nourishment Volume [m³]	Shoreface Nourishment Volume [m³]
Delfland	1991 - 2000	466384	1154193
	2001 - 2010	682290	1535404
	2011 - 2020	6033333	1333333

4 **Methods**

This chapter consists of several sections that explain the approach of this study. The sections describe the obtained data, the technique to determine and analyse nourishment longevity, the method to determine missing design aspects, and finally, the process to build and assess a multiple linear regression model.

4.1 Data

This section focuses on the obtained datasets and data processing. The data for this research is obtained from Rijkswaterstaat. The collected data is from two separate sources along the entire Dutch coast. The first dataset consists of information about the collected sand nourishments, and the second dataset contains coastal data (e.g., topography and bathymetry) recorded on an annual basis.

4.1.1 Sand Nourishment Data

For the central Holland coast, between coastal section Noord-Holland and Delfland, 175 executed sand nourishments are recorded from 1965 till 2020. This can be divided into 116 beach nourishments, 41 shoreface nourishments, and 18 other types of nourishments (e.g., dune and channel wall). In Table 4.1 a summary is given of the 175 executed sand nourishments along the central Holland coast.

Table 4.1: The number of recorded sand nourishment types along the three coastal sections (Noord-Holland, Rijnland, and Delfland).

Coastal Sections	Beach Nourishment	Shoreface Nourishment	Other Nourishment
Noord-Holland	60	21	10
Rijnland	15	12	1
Delfland	41	8	7
Subtotal	116	41	18
Total	175		

Table 4.1 shows that beach nourishments are mostly performed at all three coastal sections. Focusing on the ratio between shoreface and beach nourishments, Rijnland has the largest ratio and Delfland the smallest. This ratio gives a first indication of how often shoreface nourishments relative to beach nourishments are performed in the coastal sections.

For each of these performed sand nourishments, information about the (i) type, (ii) length, (iii) volume, (iv) execution begin/end transects, and (v) execution begin/end dates are collected. However, design aspects such as nourishment slope, nourishment height and sediment characteristics are not available (except for beach nourishments that are performed after 2010). The annual recorded cross-shore profiles can potentially determine the missing data of the design height and slope. The method will be discussed in

Section 4.5. However, no data was available in order to acquire information about the missing sediment characteristic. There is an option to appoint a sediment characteristic to the beach nourishments by finding the closest borrow area for each nourishment location. Although, this approach has many uncertainties. Therefore, it is decided to exclude sediment characteristics from this study.

Heat Map

The acquired nourishment data can be visualised with a heat map. This data visualisation technique can present a specific nourishment type in two dimensions, space and time (transect and year), with the corresponding design volume. Consequently, a quick overview can be obtained to compare individual nourishments with each order regarding the length, frequency, and design volume.

The 116 performed beach nourishments along the central Holland coast are illustrated in Figure 4.1. The beach nourishments are highlighted as horizontal bars. The length of the horizontal bars determines the beach nourishment length, and the gap in years between two successive nourishments indicate the nourishment frequency. The contrasting colours in the horizontal bars introduce the magnitude of nourishment volume. Below the heat map, a colour bar is illustrated.

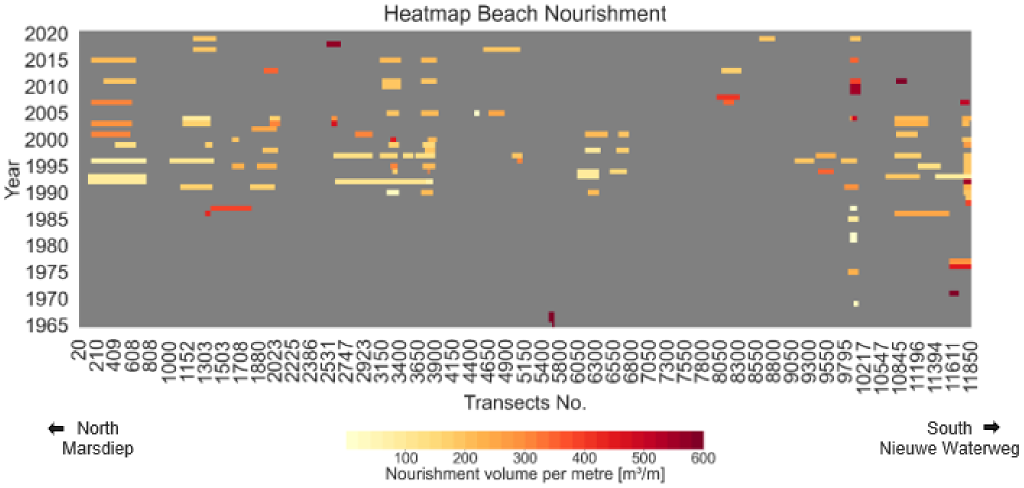


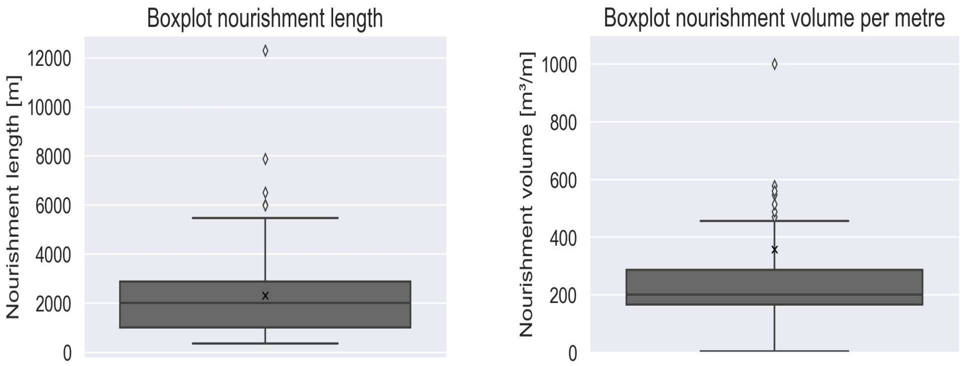
Figure 4.1: A visualisation of beach nourishment data along the central Holland coast (transect 20 - 11850) between 1965 and 2020 using a heat map. The horizontal bars present the beach nourishments and the contrasting colours indicate the magnitude of nourishment volume per unit metre.

The heat map reveals that each beach nourishment's length, frequency and volume can differ between space and time. It it is observed that for each location of interest, the lengths of the performed beach nourishments are relatively similar over decades. However, among the locations of interest, the length can vary. Besides the variation in length, the renourishment frequency can differ as well. Figure 4.1 shows an alteration of the duration interval between successive renourishments in space and time. This suggests that the nourishment frequency varies among the locations and can change through the years. The offset between nourishments presents the difference in nourishment frequency. A two-dimensional change also applies to the nourishment volume. The heat map shows that beach nourishments at different locations and times could have different nourishment volumes. It is noticed at some locations that the nourishment volumes are equivalent through the years. However, there are also locations where the nourishment volumes are altering, and no clear trend can be observed.

In summary, the location decides mainly how long the beach nourishment length should be. On the contrary, the nourishment frequency and volume vary through space and time.

Box Plot

Two box plots are presented in Figure 4.2. The box plots represent the data of 116 beach nourishments' length and volume visually. It is observed that both of the box plots are positively skewed, which means that the data is not symmetrically distributed. As a result, the mean and the median are not equivalent. The mean is indicated as an (x), and the median is the horizontal line between the lower and upper quartile. According to the box plots, common beach nourishment has a length and volume of around 2000 metres and 200 cubic metres per metre respectively. However, considering the exceptional beach nourishments, the general beach nourishment length and volume will increase to approximately 2313 metres and 356 cubic metres per metre respectively.



(a) Mean = 2313 & Median = 2000

(b) Mean = 356 & Median = 200

Figure 4.2: Box plot illustrating the mean and median of the 116 beach nourishments' length and volume per metre.

In addition to the box plots, Table 4.2 is provided to show the five-number summary and the mean. The presented values give an overview of different parts of the box plot and the degree of dispersion and skewness in the data.

Table 4.2: The five-number summary (minimum, lower quartile, median, upper quartile, and maximum) and mean are given of the 116 beach nourishments' length and volume per metre.

Elements	Nourishment Length [m]	Nourishment volume [m³/m]
Minimum	350	4
Lower Quartile	1008	166
Median	2000	200
Upper Quartile	2863	286
Maximum	12300	8995
Mean	2313	356

4.1.2 Coastal Data

In theory, the collected coastal dataset should consist of 28056 observations based on the annual measurement of 501 transects along the coast from 1965 till 2020 (56 years). However, in practice, not every transect is consistently measured and certainly in the early years. As a result, this brings the total observation to 24273. All these observations include information about the coastal indicators: (i) momentary coastline (MCL) position and (ii) beach volume. The time variations of these coastal indicators in each transect describe the evolution of the beach.

Momentary Coastline (MCL)

As stated in the introduction, the MCL position is a coastal indicator that determines the progression (retreat or advance) of the coastline over time relative to the coastline position in 1990 (BCL). This coastal indicator is developed by Hillen et al. (1991) and is used as an official coastal indicator by government institutions and studies in the Netherlands. The MCL is derived with the JARKUS data, which consists of annual measured cross-sectional elevation of the dune, beach (measured with laser altimetry), and shoreface (measured with single or multibeam sonar from a boat). In Figure 4.3 the calculation zone is illustrated in the cross-shore profile to determine the average MCL position with respect to the reference line.

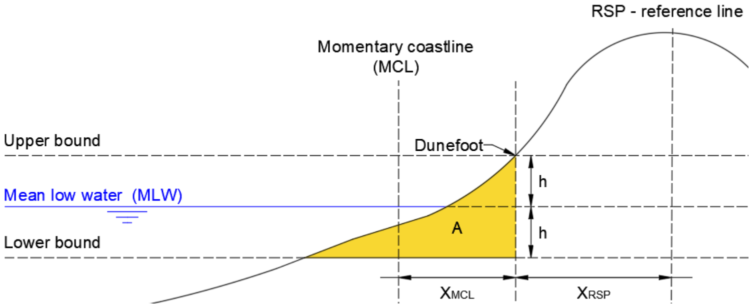


Figure 4.3: A visualisation of the calculation zone in the cross-shore profile to compute the momentary coastline (MCL) position with respect to the reference line.

With:

- h = difference between dunefoot and mean low water [m]
- A = area calculation zone [m²]
- X$_{\text{RSP}}$ = distance between dunefoot and reference line [m]
- X$_{\text{MCL}}$ = distance from MCL position to dunefoot [m] ($X_{\text{MCL}} = \frac{A}{2 \cdot h}$)

In Figure 4.3, it is noticed that the calculation of the MCL relies on the position of the dunefoot and the mean low water (MLW). These two positions determine the horizontal boundaries (upper and lower bound). In this study, the applied dunefoot or upper bound elevation is fixed at +3 metre NAP for all coastal sections. This value is commonly used for the Holland coast (van IJzendoorn et al., 2021). The lower bound in this study varies in the range of -4.4 and -4.6 metre NAP. These boundaries are used to compute the area, as indicated in the figure with the yellow colour. In combination with the area and the elevation between dunefoot and MLW, the distance between the MCL and dunefoot

(X_{MCL}) can be determined. Adding X_{MCL} with the distance between dunefoot and the reference line (X_{RSP}), will provide the MCL position with respect to the RSP. The reason to measure from the fixed reference line is to be able to compare the MCL of each year.

The equation of the MCL is as follows:

$$MCL = X_{MCL} + X_{RSP} = \frac{A}{2 \cdot h} + X_{RSP} \tag{4.1}$$

The method described above to compute MCL can give a false perception of the beach development. The false perception exists if moving sandbars are present above the lower bound of the calculation zone. The sandbars above the lower bound will add extra area to the calculation zone. According to Equation 4.1, the increase of area in the calculation zone will move the MCL position seaward. Therefore, it is certain that the seaward movement of MCL is not only caused by beach nourishment. An example is given how moving sandbars can affect the value of MCL, see Figure 4.4.

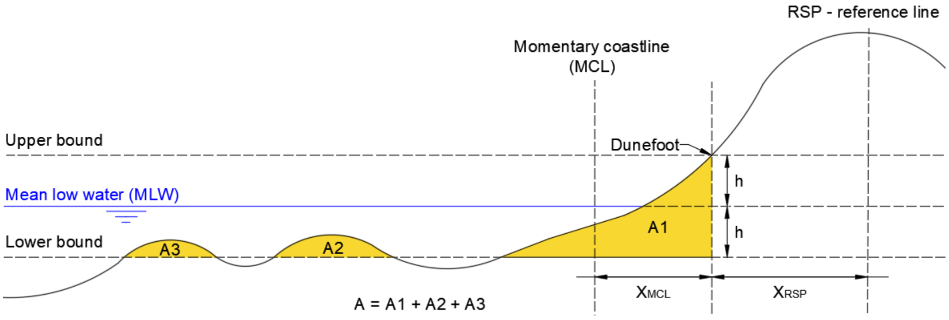


Figure 4.4: A visualisation of how moving sandbars can affect the calculation zone in the cross-shore profile and influence the momentary coastline (MCL) position with respect to the reference line.

In Figure 4.5, a first impression of the MCL data is given with a scatter graph. The applied MCL data is obtained from an arbitrary transect in Julianadorp. The MCL data shows the retreat and accretion of the coastline, which can either be natural or as a result of nourishment. Besides the MCL data, BCL data is also depicted. The combination of these two data shows when MCL exceeds BCL.

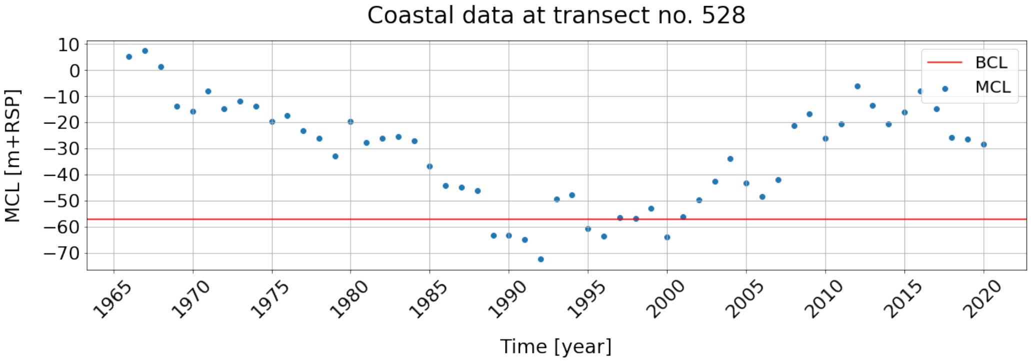


Figure 4.5: The visualisation of the coastal data (MCL) at transect no. 528 between 1965 and 2020.

Beach Volume

The beach volume is the second coastal indicator in the dataset. This coastal indicator is based upon the marked yellow area between the upper and lower boundary, as indicated in Figure 4.6. The unit of this coastal indicator is cubic metre per unit length. An increase or decrease of the beach volume indicates whether the coastline is retreating or advancing respectively. Therefore, beach volume is a suitable alternative as a coastal indicator.

As explained in the previous section, moving sandbars can influence the area of the calculation zone and thus the beach volume. To prevent this, the beach volumes should be computed with new boundaries. By moving the lower bound to an elevation of 0 metre NAP, the issue of area increase in the calculation zone due to moving sandbars can be avoided. This new elevation is where the transition starts from dry to wet beach measurement. In Figure 4.6, an example is given how the lower bound is adjusted. The yellow marked area in the cross-shore profile is the new beach volume that will be used as a coastal indicator.

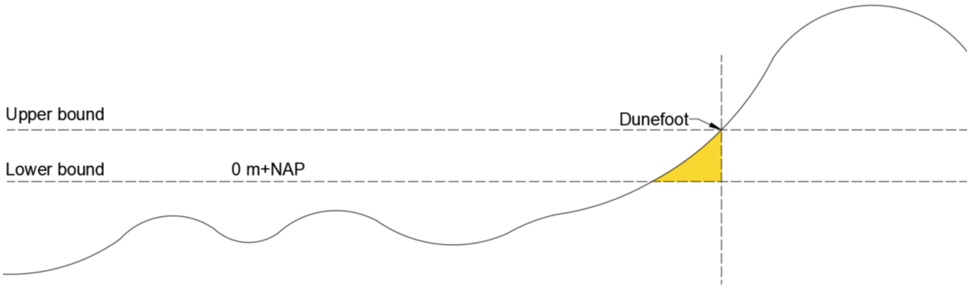


Figure 4.6: A visualisation of the adjusted calculation zone in the cross-shore profile to compute the beach volume.

To give a first impression of the beach volume data, a scatter graph is illustrated in Figure 4.7. This scatter graph presents the beach volume data at the same transect in Julianadorp as in Figure 4.5. In comparison with the previous scatter graph, it can be observed that the data of the coastal indicators do not have the same pattern. The difference in pattern is caused by the adjustment of the lower boundary.

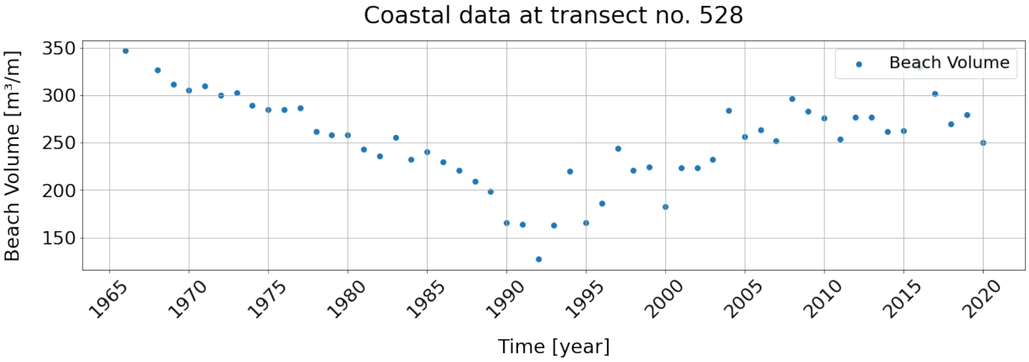


Figure 4.7: The visualisation of the coastal data (beach volume derived from new boundaries) at transect no. 528 between 1965 and 2020.

4.1.3 Storm Data

The data of storm events is obtained from the Royal Netherlands Meteorological Institute (KNMI). According to this institute, storm events occur when an hour average wind speed is equal to the winds of Beaufort force 9. The dataset of KNMI contains dates of storm events in the Netherlands since 1910. These collected data are helpful to create additional data, such as which beach nourishments are shortly applied before a storm and which beach nourishments are performed during a storm or summer season.

For this study, the additional storm data will be presented as categorical data consisting of dummy variables. This type of variable shows only the values 0 or 1 to present the absence or presence of a specific situation. By presenting the storm data in this way, it can be used as independent variables in the MLR. The sections below will explain how to transform storm data into dummy variables that present categorical data.

To determine whether beach nourishment is applied shortly before a storm, the definition of shortly must be defined. In this study, it is defined as within three months before a storm. If the storm and beach nourishment dates satisfy this assumption, a dummy variable will be added to the dataset with value 1 and otherwise 0. By doing this, a new independent variable is formed for this specific situation and can be used in the MLR model.

Another storm-related data is about which season the nourishment is performed. This data can be presented as categorical data with dummy variables. A few assumptions need to be made to create these dummy variables. For this study, it assumed that a storm season occurs in the period between October and March. In contrast, the summer season is considered in the period between April and September. If beach nourishment is carried out in the period of a storm season, the dummy variable in the dataset will have a value of 1. For the summer season, the dummy variable will have a value of 0. The dummy variables in the dataset can be used as independent variables in the MLR model.

4.1.4 Processing Nourishment and Coastal Indicator Data

The nourishment and coastal indicator datasets need to be combined into one dataset to acquire comprehensive data for analysis. In order to combine these datasets, two conditions need to be met. The transect and year of the coastal data should match with the nourishment data (transect interval and execution year). If this is the case, the nourishment data can be merged into the coastal dataset. This results in a single dataset that shows all the coastal data with the corresponding nourishment data.

4.2 Beach Nourishment Selection

Before any beach nourishments can be analysed, the 166 registered beach nourishments, as stated in Subsection 4.1.1, should be filtered by certain conditions. This is because not all of the beach nourishments will be analysed in this research since not every beach nourishment is suitable for the study. In order to answer all the research questions, it is decided that the beach nourishments should meet the following conditions for each location:

- The selected beach nourishments are not performed in two or more successive years. (Otherwise, the first sub-question can not be answered)
- Each potential location should have at least two beach nourishments to compare (Otherwise, the second sub-question can not be answered)

By filtering the beach nourishments based on the conditions above, 22 suitable beach nourishments will remain for the analysis.

4.3 Beach Nourishment Longevity

This section focuses on the longevity of beach nourishment. First the definition of beach nourishment longevity is defined. In addition, the method to determine longevity is described. Finally, it is reported how to appoint representative longevities and assess the computed nourishment longevities.

4.3.1 Definition of Longevity

The definition of longevity is crucial since it can be interpreted differently. For this study, longevity is defined as the period that the added cross-shore sediment volume (between upper and lower bound) at a specific transect is still larger than cross-shore volume prior to the implementation of nourishment. In other words, longevity is the duration that total beach volume after beach nourishment is finally reduced to the total beach volume level just before beach nourishment.

4.3.2 Method for Longevity

In the previous section, the definition of beach nourishment longevity is given. To measure the duration of the longevity, coastal indicators: (a) MCL or (b) beach volume will be used. These types of coastal indicator can represent how the beach develops over time due to erosion after a beach fill. The reason to choose these two indicators is that related studies and government institutions commonly use them. Although, other indicators such as dunefoot or beach width are applicable as well. As stated in Section 2.1, Dean (2003) proposes that the erosion rate after nourishment decays exponentially over time. Since the development of the coastal indicator is related to the erosion rate, the exponential decay feature should also apply to the coastal indicator data. Even though coastal indicator data after nourishment has an exponential function, linear regression is chosen instead of an exponential regression to represent the decay of the coastal indicator. An explanation for this approach is the limited data at several transects to perform an exponential regression. The assumption to use a linear regression is acceptable as it will result in a relatively small underestimation of the longevity that will average out in the large dataset.

A linear regression method will be used to determine the beach nourishment longevities. The linear regression attempts to fit the best linear model into the coastal indicator data after beach nourishment. It will reflect how the beach will develop after beach nourishment is carried out and therefore create a manner to determine the longevity.

In theory, it is recommended to use as much possible measured data to create the regression line that resembles the beach nourishment's effectiveness. The regression contains two quantitative variables: dependent and independent variables.

The linear regression has the following notation:

$$y = a \cdot x + b \tag{4.2}$$

The variables are as follows:

- y = dependent variable
- x = independent variable
- a = slope
- b = intercept

The dependent variable is specified as the coastal indicator data that describes the beach progress, and the independent variable represents the date of the measured data. Additionally, the slope indicates whether the beach will develop a seaward or landward trend, and the intercept shows the first coastal indicator data after beach nourishment is carried out. The sign of the regression slope is assumed to be negative as it is expected that the beach will have a landward trend after beach nourishment is executed.

To determine longevity with the regression method, the measured coastal indicator data before beach nourishment needs to be introduced. This data is not affected by beach nourishment and can therefore be used as a reference to track down how long it takes before the nourishment effect is not noticeable anymore after beach nourishment. This duration provides a new date, which relates to the end of the beach nourishment effect. By subtracting the completion date of beach nourishment with the date of no beach nourishment effect, the beach nourishment longevities in years can be derived.

A graph is used as a visual interpretation tool in order to determine the beach nourishment longevity (see Figure 4.8). In this example, the MCL data is applied as a coastal indicator instead of beach volume. In the graph, the measured MCL data is illustrated as a scatter plot, and the completion date of beach nourishment is illustrated as a yellow vertical line. The MCL migrated significantly seawards after beach nourishment was carried out. However, as the years passed by, the MCL position is decreasing. To represent the decay of the MCL positions, a linear regression line is added to the graph. The regression line is based on the annual MCL data after the completion of beach nourishment, of which the beach volume is larger than the beach volume of the MCL reference data point. In addition, an extra year of MCL is used, where the beach volume is smaller than the beach volume of the MCL reference data point.

The combination of the regression line, the beach nourishment completion date, and the measured MCL position before beach nourishment is the solution to determine the longevity. The beach nourishment longevity is illustrated with a green distance arrow, as shown in Figure 4.8.

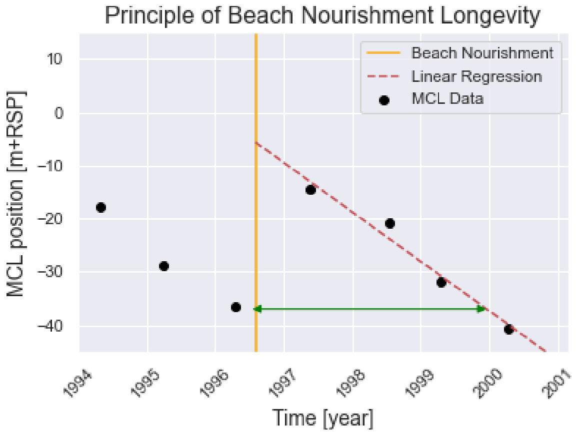


Figure 4.8: A graph to determine the beach nourishment longevity at an arbitrary transect. The following aspects are presented: the coastal indicator data (black dots), the completion date of beach nourishment (yellow vertical line), linear regression (red dashed line), and beach nourishment longevity (green distance arrow).

4.3.3 Appoint Representative Nourishment Longevity Value

In order to appoint a representative longevity value for beach nourishment, the method described above should be applied for multiple transects where the nourishment is performed. This is because, along the coastal section, the cross-shore profiles of the transects vary and result in different longevity among these transects. Therefore, using only one transect to determine the longevity can never sufficiently represent the beach nourishment longevity. The number of transects that will be used depends on the beach nourishment length and the choice of transect interval size. In general, a transect interval between 250 and 500 metres will be applied.

To find the representative longevity value for the nourishment, the median will be calculated for all the derived transect longevities of specific nourishment. By taking the median, the outliers will be omitted, resulting in an adequate value representing better the beach nourishment longevity.

4.3.4 Confidence Assessment of Nourishment Longevity

To assess whether the determined nourishment longevities are sufficient enough for analysis. A confidence assessment is conducted. This assessment assigns a confidence level to the determined longevity values for each transect. The assessment is necessary because not every longevity is determined in the way it should be due to the coastal morphology that has affected the JARKUS data. The confidence level has in total three categories: high, moderate and low. A high confidence level indicates a correctly computed nourishment longevity, while a moderate confidence level indicates that the computed longevity is questionable due to data. Finally, a low confidence level proposes that the computed longevity is unreliable due to insufficient data.

The confidence levels for assessing the beach nourishment longevities are listed below with a concise description:

- **High confidence level**: the beach nourishment longevity is computed with a regression line that is based on the monotonic decrease of coastal indicator data.
- **Moderate confidence level**: the beach nourishment longevity is determined with a regression line that is based on only two coastal indicators or/and where the regression line is affected by the increase of the coastal indicator data after beach nourishment is carried out.
- **Low confidence level**: the beach nourishment longevity is computed with the same properties as the moderate confidence level. However, in addition to the latter, no eligible reference data point can be appointed. This is due to no cross-shore profile measurement of that year or questionable reference data point as it is affected by morphology.

Examples of Confidence Level

In this section the examples of different situations are illustrated to explain the three confidence level.

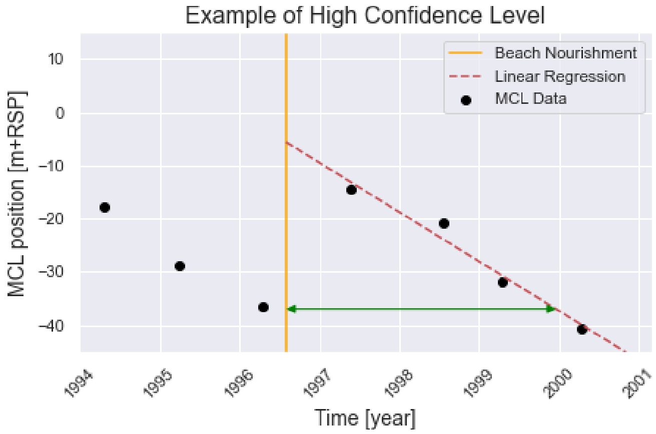


Figure 4.9: An example of beach nourishment longevity labelled with a high confidence level. The data points of coastal indicator (black dots) are decreasing monotonically after the completion of beach nourishment (yellow vertical line). The regression line fits the coastal indicator data well. Consequently, there is a high confidence that the beach nourishment longevity is computed correctly.

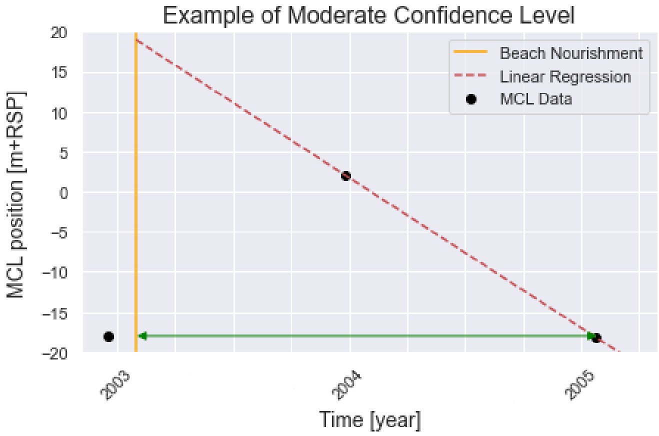


Figure 4.10: An example of beach nourishment longevity labelled with a moderate confidence level. The regression line to compute beach nourishment longevity is based on two coastal indicator data points. The limited amount of data points for the regression line makes the computed beach nourishment longevity questionable.

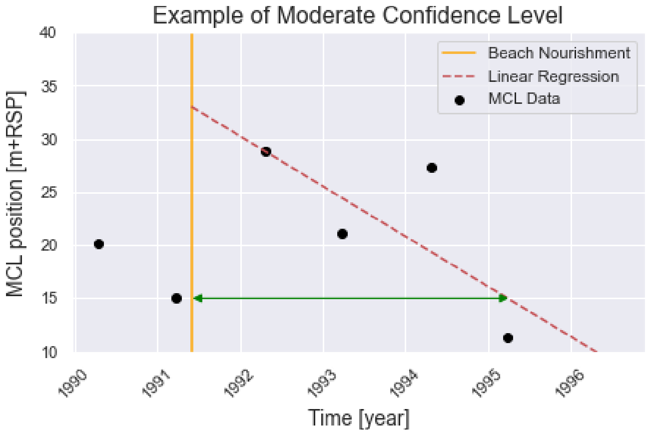


Figure 4.11: An example of beach nourishment longevity labelled with a moderate confidence level. The data points of the coastal indicator (black dots) are not decreasing monotonically after the completion of beach nourishment (yellow vertical line). It can be observed that a data point of the coastal indicator has increased after beach nourishment is carried out. The random increase affects the position and slope of the regression line. Consequently, the computed beach nourishment longevity is questionable.

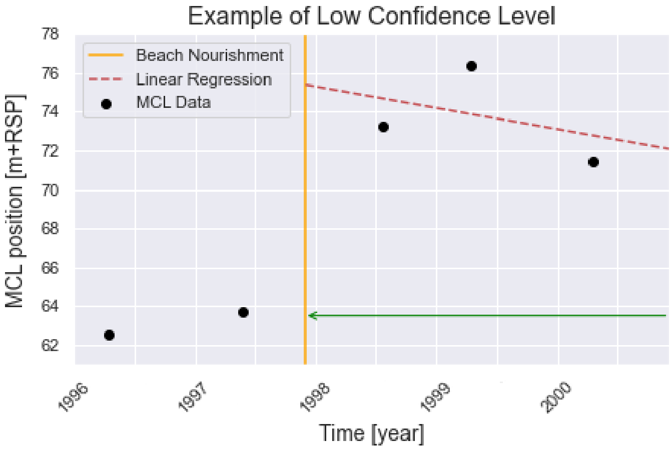


Figure 4.12: An example of beach nourishment longevity labelled with a low confidence level. As can be seen, the data points of the coastal indicator (black dots) have the same properties as the latter moderate confidence level situation. In addition, the reference data point (black dot of 1997) in this figure is questionable since it has increased compared to a year before. As a result, the confidence of the computed beach nourishment longevity is low.

4.3.5 Overview

A flow chart is illustrated in Figure 4.13. This flow chart provides an overview of all the steps described in the previous sections.

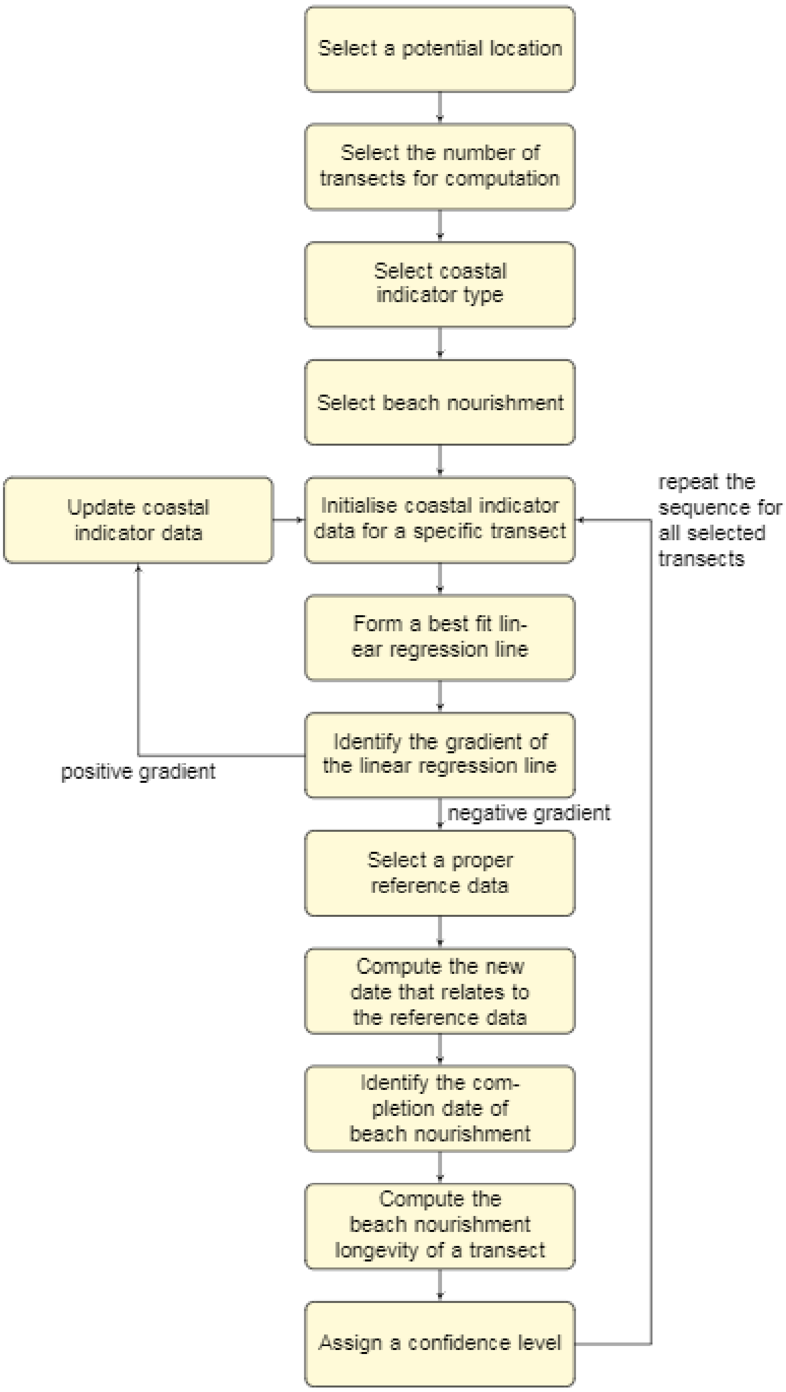


Figure 4.13: A flow chart illustrating the process to determine beach nourishment longevities along central Holland coast.

4.4 Analyse Beach Nourishment Longevities

In the previous section, it is described how to determine the beach nourishment longevities. This section explains the methods to analyse the longevity values to gain insight into longevity per location, the development of beach nourishment longevities over time, and shoreface nourishments' effect on beach nourishment longevities.

4.4.1 Average Beach Nourishment Longevity per Location

The average beach nourishment longevity of each location can be computed by taking the median longevity value of all performed beach nourishments in the location. The reason to choose the median instead of the mean is to filter out possible outliers. The derived median longevity values show how the beach nourishment longevities differ among the locations.

4.4.2 Development of Beach Nourishment Longevities

In order to conclude how the beach nourishments along the central Holland coast have developed over time, all the determined beach nourishment longevities will be sorted into four time intervals (1990-1994, 1995-1999, 2000-2004, 2005-2020). For each time interval, the median of the longevities will be computed. The reason for these four intervals is to obtain enough longevity values to compute a representative median value. Besides, in Section 3.3, it was mentioned that shoreface nourishments became a common practice in 2000. By doing this, a distinction can be made whether beach nourishment longevities are derived before or after shoreface nourishments became relevant. For the last time interval, a different time range is chosen because the number of performed beach nourishments has decreased significantly during those years. To successfully analyse the longevity development, it is decided to choose a time interval range from 2005 to 2020 to collect enough longevity values. The obtained longevity value for each time interval will explain how the beach nourishments have developed through the years.

As stated in Section 2.4, shoreface nourishments could positively affect the development of beach nourishments. Therefore, it is also essential to analyse how shoreface nourishments (from 2000) contribute to the beach nourishment longevities. The analysis will be performed with a statistical graph 'grouped boxplots'.

The approaches that are described above enhance the understanding of beach nourishment development from 1990 till 2020.

4.5 Method for Obtaining Nourishment Design Parameters

As mentioned in Subsection 4.1.1, the nourishment's height and slope are missing for each beach nourishment. To obtain this data, JARKUS cross-shore profiles of the central Holland coast are used. With these profiles, the unknown design aspects of beach nourishment can be determined. In the JARKUS cross-shore profiles, a clear difference can be noticed when beach nourishments are applied. The distinctive features after a beach fill are the unnatural slope, flat berm and increased sediment volume. In Figure 4.14, an example is given of two JARKUS profiles where the features are noticeable.

Figure 4.14: Two JARKUS cross-shore profiles are depicted of an arbitrary transect, where distinctive features of the beach nourishment (performed 2005) are indicated in the cross-shore profile of 2006.

The cross-shore profile of May 2006 shows the effect of the beach nourishment performed in April 2005. It can be observed that beach nourishment has resulted in extra beach volume with a wide flat berm and a steep slope. Profiles that present such features are suitable for determining the design height and design slope. The methods to derive the unknown design aspects are outlined below.

4.5.1 Design Height

The elevation of the design height is indicated in the cross-shore profile graph. The flat horizontal line in the cross-shore profile is a typical feature to identify the design berm of beach nourishment. The most effective way to determine the design height is to find the flat berm in the cross-shore profile and read the berm crest elevation from the y-axis of the graph. In Figure 4.15, the berm crest is located at the elevation of +4.5 metre NAP. The elevation of this flat berm is the beach nourishment's design height at transect no. 3725.

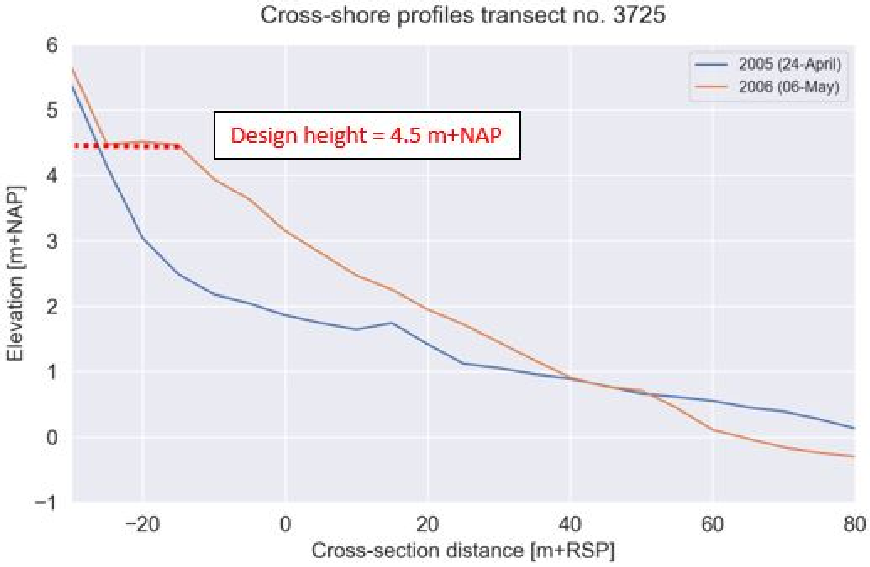


Figure 4.15: A cross-shore profile of an arbitrary transect to determine the design height of a beach nourishment.

4.5.2 Design Slope

The slope of the beach nourishment can be determined by plotting the best fit line in the cross-shore profile that is affected by beach fill. The straight line starts at the cross-section distance where the design of the flat berm stops and will end at the cross-section distance where the cross-shore profiles intersect each other. The x and y coordinates at the start and end of the line are essential to derive the slope. In Figure 4.16, the start and end positions are visualised with a green and yellow circle. The coordinates (X1 & Y1) of the green circle are located at the berm crest's end. The coordinates (X2 & Y2) of the yellow circle are determined by finding the intersection point of the two cross-shore profiles.

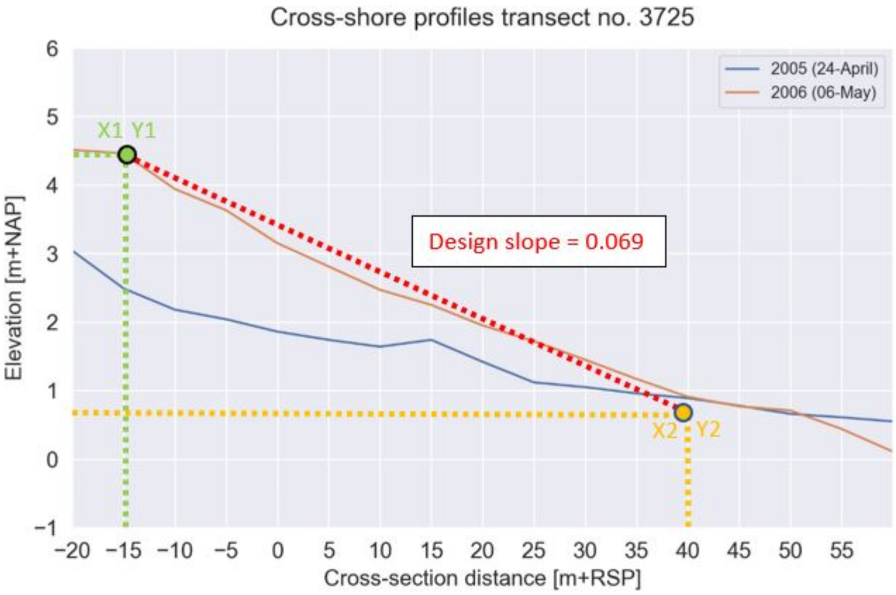


Figure 4.16: A cross-shore profile of an arbitrary transect to determine the design slope of a beach nourishment.

Using the changing x and y coordinates the slope can be determined. The design slope has the following equation:

$$design\ slope = \frac{\Delta Y}{\Delta X} = \frac{Y2 - Y1}{X2 - X1} \tag{4.3}$$

Based on the coordinates in Figure 4.16 and Equation 4.3, it will result in a design slope of 0.069.

To ensure that the above method is valid to use, the documented official design slope in the design report is used as a reference to compare with the computed design slope. One of the available design reports is from Julianadorp in 2016. Figure 4.17 gives an illustration of how it is compared. The figure shows cross-shore profiles of an arbitrary transect, where the beach nourishment of 2016 is performed in Julianadorp. Furthermore, it shows the official design slope (black dashed line), the actual measured slope (red dotted line) and the trend line of the measured slope (grey dashed line).

In Figure 4.17, it is noticed that the official design slope is far from equivalent to the actual measured slope. The official design slope (1:30) is very gentle compared to the trend line of the actual measured slope (1:15). Therefore, it is concluded that the determined design slope with the described method is too uncertain. As a result, it is decided that the design slope will not be used anymore in the MLR model.

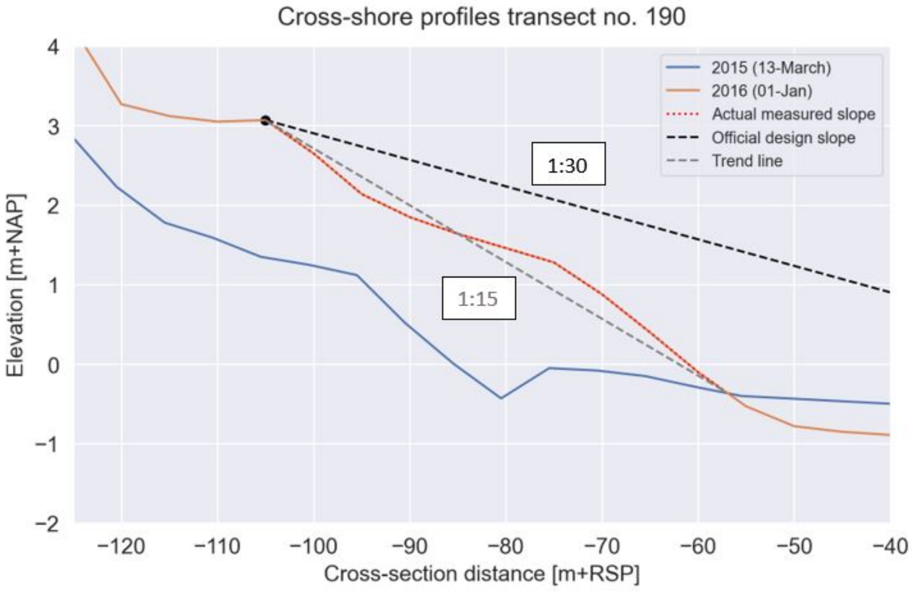


Figure 4.17: A cross-shore profile of an arbitrary transect to determine the difference between the official and actual measured slope.

4.5.3 Appoint Representative Design Aspect Values to Nourishment

The derived design height and slope from only one transect can not be appointed as the valid design aspects for beach nourishment. One transect could represent the design aspect values of beach nourishment. However, it is better to compare various design aspect values of different transects to be more confident. Therefore, to compute the representative design aspects for each beach nourishment, the design aspects should be determined for a few transects where the beach nourishment is performed. The number of transects will depend on the nourishment length. It is decided to use at least three transects in the section where beach nourishment is carried out. The first transect is located at the middle of the beach nourishment, and the other two transects are located a few hundred metres from the left side and right side of the first transect. This approach will increase the validity of the design aspects. In order to find the representative design height and slope of the beach nourishment, the mean value of the determined design aspects from different transects should be determined.

4.5.4 Confidence Assessment of Design Height

The described method to find the design aspects has a certain degree of uncertainty as it is determined manually based on coastal data. Errors could occur due to misreading the graph or not having the correct data. The largest errors in the data are possibly created by the morphological changes between the moment of beach nourishment execution and the first measurement. Consequently, some identified design aspects in the transects could be insufficient for analysis. A confidence assessment will be conducted to ensure that only suitable design aspects are selected for further analysis. The assessment will assign a confidence level for each transect's design height and slope. This will indicate how well the design aspects are determined. There are three categories for the confidence level: high, moderate and low. The first confidence level implies that the design aspects are determined as described above. The second confidence level suggests that the determined design aspects are arguable because no flat berms are depicted to read the design heights. Instead, the design heights are determined when the cross-shore profiles start to separate due to nourishment. Finally, the last confidence level proposes that the design aspect can not be used since it is determined with too much uncertainty. For the design aspects, it decided to use only design aspects that are labelled with a high and moderate confidence label. Design aspects with a low confidence level have excessive error and are therefore not proper to use. The design heights with a moderate confidence level are acceptable since the effect of beach nourishment is noticeable. The berm elevation of the beach nourishment is still partially visible in the cross-shore profile.

4.6 Multiple Linear Regression

The statistical method, multiple linear regression (MLR), is commonly used in various studies to understand the complex relationship between variables. The MLR model can be applied when it involves more than one independent variable. The model predicts the linear relationship between the independent and the dependent variables. As a result, it identifies the effect of the independent variables on a dependent variable. Since this study focuses on how nourishment design aspects (independent variables) affect the beach nourishment longevity (dependent variable), a multiple linear regression is an appropriate method.

4.6.1 Regression Principles

In the section below, the principles about MLR are explained to understand the model for estimating the regression coefficient.

The MLR has the following general equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \epsilon \tag{4.4}$$

Where:

- y = dependent variable
- x_i = independent variable (i = 1,2,...,n)
- β_j = regression coefficient (j = 0,1,...,n)
- ϵ = error term / residuals

In this study, (y) denotes the nourishment longevity and (x_i) denotes the nourishment design aspects. Each design aspect has its regression coefficient. These regression coefficients are denoted as (β_j). In Equation 4.4, a single (β_0) is given. This regression coefficient is the intercept of the regression plane and does not have a physical interpretation. However, the other regression coefficients measure the expected change between (y) per unit change (x_i). The error term is denoted as (ϵ). This term shows other factors that influence the dependent variable besides the independent variables.

In order to use the MLR model, it is more convenient to express Equation 4.4 in matrix notation. The matrix notation is shown in Equation 4.5.

$$\hat{y} = X\hat{\beta} + \hat{\epsilon} \tag{4.5}$$

Where:

$$\hat{y} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{1,1} & x_{1,2} & \cdots & x_{1,m} \\ 1 & x_{2,1} & x_{2,2} & \cdots & x_{2,m} \\ 1 & x_{3,1} & x_{3,2} & \cdots & x_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n,1} & x_{n,2} & \cdots & x_{n,m} \end{bmatrix} \quad \hat{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix} \quad \hat{\epsilon} = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

In Equation 4.5 two subscripts are presented. The first subscript (n) in the matrix notation denotes the unit of observations of the dependent variable, and the second subscript (m) denotes the number of independent variables. In this matrix notation, the values of the dependent $(\hat{y})$ and independent (X) variables are known, except for the regression coefficients $(\hat{\beta})$ and error terms $(\hat{\epsilon})$.

By using the method, ordinary least squares (OLS), the unknown regression coefficients $(\hat{\beta})$ in the regression model can be estimated. OLS used the principle of least squares to minimise the difference between the sum of squares of the actual and predicted dependent variables. This way, a better model will be generated to fit the data. Moreover, in the method of least squares, it is assumed that the mean of the residuals is zero, the variance is constant, and the residuals are uncorrelated. Consequently, Equation 4.6 can be expressed to determine the regression coefficients.

$$\hat{\beta} = (X^T X)^{-1} X^T \hat{y} \tag{4.6}$$

For this study, a statistical software package (scikit-learn) in Python will be used to run the MLR model with the OLS method as described above. This way, a more complex MLR model can be solved. Moreover, the computations are much faster and less prone to computational error.

4.6.2 Regression Assumptions

Before building a MLR model in Python, it is essential to test a few assumptions. These assumptions can not be violated. A violation of the assumption can result in a biased estimate of relationships, unreliable regression coefficients, uncertain confidence intervals, and uncertain significant test (Williams et al., 2013). Consequently, this means that the model does not fit the data well and is therefore not recommended to apply. These assumptions will be tested with existing Python libraries.

The MLR model should satisfy the following assumptions:

- A linear relationship is assumed between the dependent and independent variables.
- No outliers in the dataset
- The independent variables are not highly correlated (absence of multicollinearity in the model)
- The residuals are homoscedastic (no heteroscedasticity).
- No autocorrelation in the error term.
- The residuals must be normally distributed.

Linear Relationship Between Variables

The first assumption is that dependent and independent variables should have a linear relationship. The linear relationship between the variables can be examined by plotting each independent variable against the dependent variable in a scatter plot.

No Outliers

The highly unusual data in the dataset, also called outliers, can strongly influence the MLR model. Therefore, outliers in the data should be analysed. Outliers are not necessarily a problem. However, outliers that are resulted from measurement or derivation error can have a severe effect on the regression analysis. Three times the standard deviation from the mean (cut-off value) will be used to detect the outliers. If the data points exceed the cut-off value, it is most likely that these points are outliers. In this case, it is recommended to remove this data.

No Multicollinearity

In a MLR model, no multicollinearity is assumed. Multicollinearity appears in a model when two or more independent variables are highly correlated (Daoud, 2017). Due to the high correlation among the independent variables, the standard error of the regression coefficient will increase. Consequently, the variance of the regression coefficients is inflated. The problem with multicollinearity in a model is that the estimated regression coefficient tends to be unreliable. The model can not effectively distinguish the highly correlated independent variables. As a result, it can not identify which independent variable has more effect on the dependent variable (Montgomery et al., 2021). In order to prevent the multicollinearity problem, one of the highly independent variables should be removed from the model.

A simple way to discover whether multicollinearity occurs in the model is by applying a correlation matrix. If a correlation of 0.8 occurs between variables, it is expected that these variables are highly correlated (Strand et al., 2011). The variance inflation factors (VIFs) approach can be used to be more confident. This method determines how each particular independent variable is contributing to the standard error in the model. The highly correlated independent variables will expose significant VIFs values. In general, it is suggested to remove the variable from the model with a VIFs value of 5, or higher (Daoud, 2017).

Homoscedasticity

Another assumption for a MLR model is homoscedasticity (no heteroscedasticity). This assumption holds when the variance of the residuals is constant at each point in the model (Cook and Weisberg, 1983). The consequence of heteroscedasticity is that regression coefficients are underestimated due to an increase of the variance. Moreover, the confidence interval and t-statistics are no longer valid. To test homoscedasticity, the Breusch-Pagan test can be used (Wooldridge, 2012). This is a hypothesis test where the goal is to reject the alternative hypothesis (variance of the residuals are not equal) and accept the null hypothesis (variance of the residuals are equal). If the p-value of the Breusch-Pagan test is larger than 0.05, it suggests that there is no heteroscedasticity (Esobari, 2012).

No Autocorrelation

The absence of autocorrelation is the following assumption that needs to be satisfied. Autocorrelation is a characteristic when a serial error term becomes correlated. As a result, the independent variables are not adequately explaining the behaviour of the dependent variable (Del Águila and Benítez-Parejo, 2011). Various reasons can result in autocorrelation, such as measurement errors of the dependent variable, important variables are omitted in the model and specify incorrectly the functional form of the relationship between variables (Huitema and Laraway, 2006). A correlogram can be used to determine whether the set of data is autocorrelated or not. Autocorrelation is absent if the data points are scattered randomly in the correlogram without any pattern (Brooks, 2019).

Normally Distributed Residuals

The final assumption is that the error term is normally distributed. This assumption decides whether the error rates are acceptable to use. If the residuals are not normally distributed, the significant test and confidence interval will be unreliable (Williams et al., 2013). A quantile-quantile (Q-Q) plot can be used to check if residuals are normally distributed (Filliben and Heckert, 2012). The Q-Q plot is visualised by plotting the residuals against the theoretical values from the standard normal distribution. To examine whether the residuals are normally distributed, a straight line is added in the Q-Q plot, where the residual values are equal to the theoretical values from the standard normal distribution. The residuals are normally distributed when all the plotted data points are located close to the straight line.

4.6.3 MLR Model Assessment

Once the MLR model meets all the assumptions, the model can be created in Python. Before running the model, input data (dependent and independent variables) based on the confidence assessment must be decided for the model. The output of the MLR model provides a comprehensive summary table with statistical values associated with the multiple regression (e.g. R-squared, F-statistic, and t-statistic). The essential statistical values are described below to gain insight into the model. Moreover, it helps to examine whether the determined regression coefficients are sufficient to describe the relationship between nourishment longevity and design aspects.

R-squared

The R-squared value gives the fraction of how much the independent variables explained the changes in the dependent variable (Wooldridge, 2012). The value always lies between zero and one. Based on the magnitude of the value, it shows how well the model fits the data. An R-squared value that equals one suggests that regression fits the data perfectly. Whereas an R-squared value that equals zero suggests that the regression fits the data poorly. To interpret the R-squared value more easily, it can be multiplied by hundred to convert the value into a percentage. This value is the percentage of the dependent variable that is explained by the independent variables. It is favourable to obtain a high R-squared value in order to be more confident in the MLR model.

Adjusted R-squared

The adjusted R-squared is a modified version of R-squared and indicates how the model fits the data by adding new independent variables (Wooldridge, 2012). Adding new independent variables always tends to increase the R-squared value. However, the increase of the R-squared value is not always justified since some independent variables can be insignificant for the model. The adjusted R-squared statistics can determine how significant the independent variables are in the model. An adjusted R-squared value that turns close to the R-squared value suggests that the included independent variables are relevant for the model. On the contrary, when the adjusted R-squared value deviates from the R-squared value, it proposes that some of the independent variables are irrelevant. If this is the case, it is recommended to remove the insignificant variables.

F-test

The F-test is used to test whether the independent variables are jointly significant in the regression model (Wooldridge, 2012). To test the overall significance of the regression, the probability value determined from the F-statistic should be used. This probability value decides whether the null or alternative hypothesis should be rejected. The null hypothesis (4.7) and the alternative hypothesis (4.8) of the F-test are formulated as follows:

$$H_0 : \beta_1 = \beta_2 = \ldots = \beta_k = 0 \tag{4.7}$$

$$H_1 : \beta_j \neq 0 \tag{4.8}$$

The null hypothesis states that none of the regression coefficients (x_k = number of independent variables) affects the dependent variable. While the alternative hypothesis suggests that at least one regression coefficient (j = corresponds to any of the k independent variables) affects the dependent variable. The independent variables in the regression model are jointly significant if the null hypothesis is rejected. In order to reject the null hypothesis, the probability value of the F-test should be smaller than the significance level of 0.05 or 5% (Wooldridge, 2012). If the null hypothesis can not be rejected, it implies that other independent variables should be introduced to explain the dependent variable.

t-test

The t-test is an essential method to assess whether the individual determined regression coefficient is significant or not (Wooldridge, 2012). To do this the null and alternative hypotheses will be tested with the p-value, which is derived from the t-statistic. The null hypothesis (4.9) and the alternative hypothesis (4.10) of the t-test are formulated as follows:

$$H_0 : \beta_j = 0 \tag{4.9}$$

$$H_1 : \beta_j \neq 0 \tag{4.10}$$

The null hypothesis suggests that β_j (j = corresponds to any of the k independent variables) does not affect the dependent variable. Whereas the alternative hypothesis proposes that β_j affects the dependent variable. The null hypothesis will be rejected if the p-value of the t-statistic is smaller than the significance level of 0.05 or 5% (Wooldridge, 2012). If the t-test fails to reject the null hypothesis, it implies that the regression coefficient of the independent variable is insignificant for the regression model.

4.6.4 Overview

A flow chart is depicted in Figure 4.18. This flowchart gives a process overview as described above to obtain a suitable MLR model for the regression coefficients.

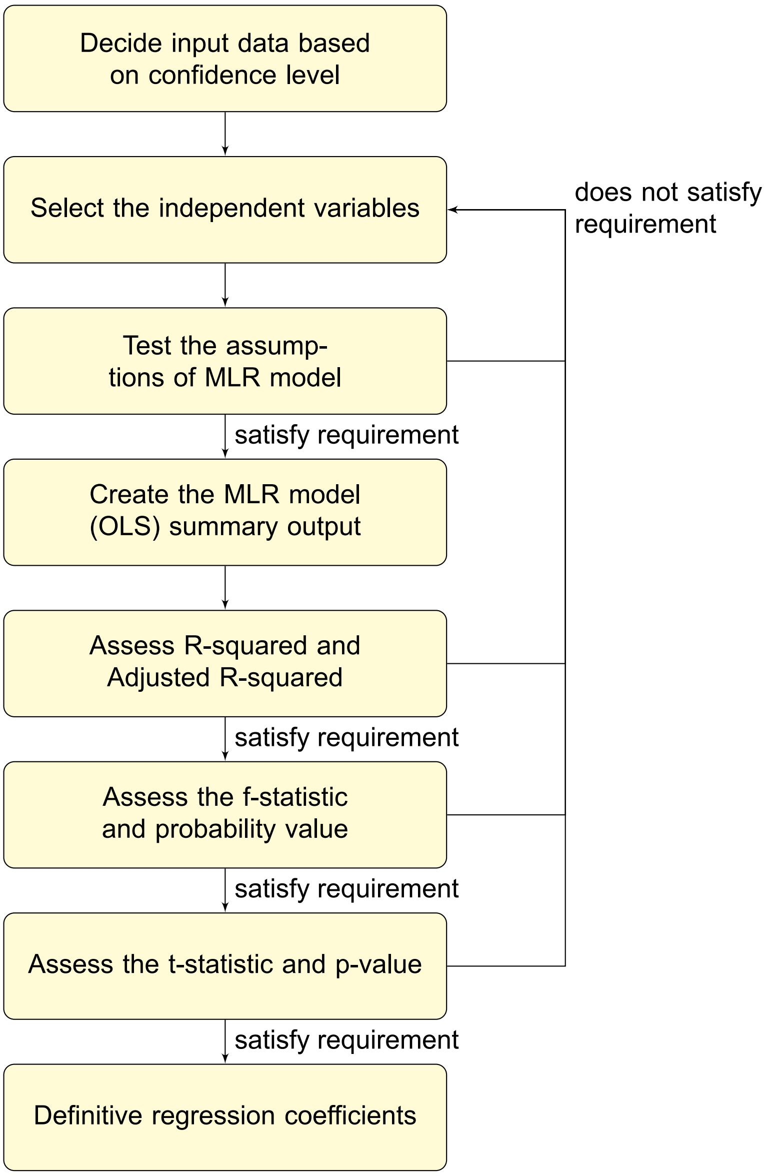


Figure 4.18: A Flow chart illustrating the process to obtain a MLR model to determine the definitive regression coefficients.

4.7 Standardise Independent Variables in the Dataset

When all the dependent and independent variables are determined and merged into one dataset, it is crucial to be aware that this dataset can not immediately be applied in a MLR model. The independent variables have different units of measurement and thus a different range. Applying the original values into the model will result in a model that responds incorrectly since some independent variables will dominate the other variables due to different scales. In order to transform the data into similar scales, the independent variables need to be standardised (Wooldridge, 2012). Re-scaling the independent variables will result in a zero mean and unit variance. The standardisation (re-scaling) of the dataset can be performed with the statistical software package (scikit-learn) in Python.

5 Results

This chapter contains the findings of the beach nourishment longevity analysis, the determined design aspects, and the procedure and results of the multiple linear regression model.

5.1 Selected Beach Nourishments

For this research, 22 beach nourishments along the central Holland coast were selected for analysis. The selection of the beach nourishment was in accordance with the method described in Section 4.2. The considered beach nourishments along the central Holland coast were divided as follows: 13 beach nourishments are from coastal section Noord-Holland, 2 beach nourishments from coastal section Rijnland, and 7 beach nourishments from coastal section Delfland, see Table 5.1 for a detailed overview.

The potential locations, Zandvoort and Noordwijk, were not included in the table as the corresponding data (coastal indicator data) was insufficient to compute longevity. The most common issues were the positive regression slopes and no suitable reference data.

Besides, the table shows the number of transects for each location. Based on the number of transects and beach nourishments, 137 longevity values in total can be determined.

Table 5.1: The selected beach nourishments and the number of transects per location.

Coastal Sections	Locations	Number of Transects	Beach Nourishments
Noord-Holland	Julianadorp (170 - 528)	7	1992
			1996
			2003
			2015
	Callantsoog (1137 - 1340)	8	1991
			1996
			2004
	Bergen aan Zee (3175 - 3275)	4	1992
			2005
			2010
	Egmond aan Zee (3725 - 3800)	7	1999
			2005
			2011
Rijnland	Bloemendaal aan Zee (6175 - 6300)	6	1990
			1993
Delfland	Scheveningen (9925 - 10075)	4	1975
			1987
			1991
			1996
	Ter Heijde (11034 - 11244)	8	1986
			1993
			1997

5.2 Beach Nourishment Longevities

In this section, the results of the computed longevities (MCL and beach volume) are indicated with the corresponding confidence level.

5.2.1 Longevity Results and Confidence Levels

Tables 5.2 and 5.3 show the longevity per transect (derived from MCL and beach volume) of the considered beach nourishments in Julianadorp. In these tables, it is observed that the confidence level of each longevity value is indicated with colour. Below each table, the median value (derived from longevities with a high confidence level) is presented for each beach nourishment. These values show the representative longevity of each beach nourishment. In addition, the average beach nourishment longevity per location is given. This value was determined by taking the median of the representative beach nourishment longevities. For the results of the other locations, see Appendix A.

Table 5.2: Beach nourishment longevities of Julianadorp based on MCL in years.

Julianadorp	Year			
Transect	1992	1996	2003	2015
170	🟩 3.18	🟩 3.31	🟩 2.44	🟩 2.49
230	🟩 4.91	🟩 3.47	🟩 4.22	🟩 3.74
289	🟨 5.92	🟩 2.52	🟨 2.67	🟩 4.83
369	🟨 5.33	🟩 4.83	🟨 2.73	🟩 1.92
429	🟨 3.15		🟨 2.06	🟩 2.01
489	🟩 1.90		🟩 2.44	🟨 2.40
528	🟩 4.64		🟩 1.96	🟨 1.40

Med$_n$ Beach	3.91	3.39	2.44	2.49
Med$_n$ Location	2.94			

Table 5.3: Beach nourishment longevities of Julianadorp based on beach volume in years.

Julianadorp	Year			
Transect	1992	1996	2004	2015
170	🟩 2.32	🟩 2.68	🟩 3.10	🟩 3.93
230	🟩 4.11	🟩 3.73	🟨 3.93	🟥 8.33
289	🟥 25.84	🟨 3.68	🟨 3.18	🟩 6.43
369	🟨 3.78	🟨 4.24	🟨 4.07	🟨 6.07
429	🟨 2.38		🟨 3.73	🟩 5.31
489	🟨 2.48		🟨 3.74	🟨 3.50
528	🟨 1.97		🟨 2.99	🟩 3.33

Med$_n$ Beach	3.22	3.21	3.10	3.93
Med$_n$ Location	3.21			

Confidence level	🟩 High	🟨 Moderate	🟥 Low

All the longevities were computed according to the method described in Subsection 4.3.2. Based on all the longevity results (see Appendix A), It can be concluded that each location consisted of some longevities that were labelled with a high confidence level. This label represents the correct determination of the longevities based on the method. Besides longevities with a high confidence level, some longevities were labelled with a moderate or low confidence level.

It was noticed that the longevities labelled with a moderate confidence level were often based on regressions that only consisted of two coastal indicator data. This amount of data points were inadequate to make sure that the longevities were determined correctly. Another situation where longevities received a moderate confidence level was when some coastal indicator data increased after beach nourishment was carried out. Intuitively, this phenomenon was unexpected since it was anticipated that the beach was eroding. Due to this phenomenon, the regression lines were more gentle than expected and resulted in longer longevities. Consequently, this made the computed longevities in these cases questionable.

The tables show that some longevities were labelled with a low confidence level. This level was reached when moderate-level issues occur and no eligible reference data could be appointed to determine longevity. The combination of these issues resulted in unreliable longevity values.

Some cells in the table were left blank as the longevities at some transects could not be determined due to unfitting data. The most common issues were positive regression slopes and the fact that no reference data were available. Both of these issues made it impossible to compute longevity.

5.2.2 Subaerial Beach Volume

As mentioned in Subsection 4.1.2, the beach volume data was modified before computing the longevity. This modification should prevent the increase of coastal indicators due to moving sandbars. However, the new beach volume dataset still showed the same issues. The data indicated that some beach volumes increased after the performance of beach nourishments. As a result, it could be concluded that other natural phenomena might also increase the coastal indicator after beach nourishments were carried out.

5.2.3 Number of Confidence Level

In Table 5.4, the total number of transect longevities of each confidence label is presented. In total, 128 transect longevities were computed with the MCL data and 122 transect longevities with the beach volume data. The longevities related to MCL were more frequently labelled with a high confidence level than those related to beach volume. Furthermore, the table also shows that the number of longevities labelled with a moderate confidence level was significant for both coastal indicators. In addition, it was remarkable that even after modifying the beach volume data, more longevities were labelled with a moderate confidence level. Based on this overview, it was decided to use the longevities derived from the MCL data since most longevities were labelled with a high confidence level.

Table 5.4: Overview of total number of transect longevities per confidence label.

Confidence Label	**MCL**	**Beach Volume**
High confidence	56	37
Moderate confidence	73	78
Low confidence	5	7
Total labels	128	122

5.3 Average Beach Nourishment Longevity per Location

In Table 5.5, all the computed median values per location from Appendix A are presented. The longevity of the central Holland coast was found to be approximately in the range of 3 and 3.5 years. The computed longevities for both coastal indicators showed similar values, except the one located at Bloemendaal aan Zee. An explanation for this observation might be the fact that this location only used two beach nourishments for comparison, and most of the computed longevities consisted of a moderate or low confidence level.

Table 5.5: The median values of beach nourishment longevities per location.

Coastal Section	**Location**	**Transect**	**Average Longevity per Location**	
			MCL	Beach Volume
Noord-Holland	Julianadorp	170 - 528	2.94	3.21
	Callantsoog	1137 - 1340	3.18	3.21
	Bergen aan Zee	3175 - 3275	2.62	3.14
	Egmond aan Zee	3725 - 3800	3.77	3.92
Rijnland	Bloemendaal aan Zee	6175 - 6300	1.68	5.32
Delfland	Scheveningen	9925 - 10075	3.13	3.47
	Ter Heijde	11034 - 11244	3.75	3.21

5.4 Development of Beach Nourishment Longevities

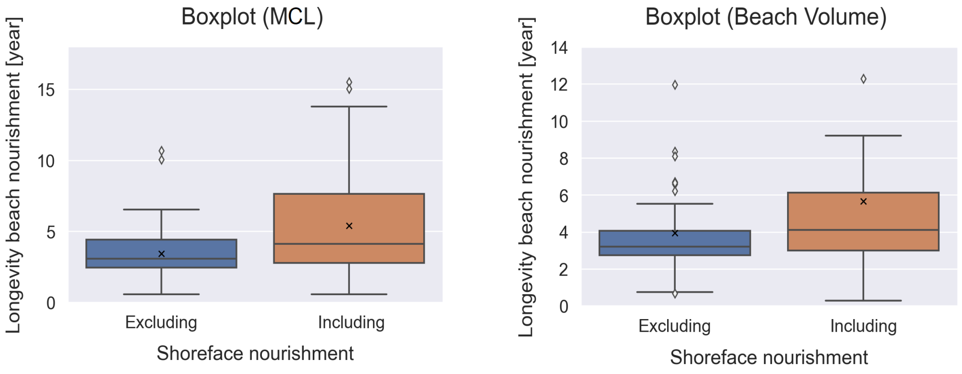
The development of beach nourishment longevities through time along the central Holland coast are presented in Table 5.6. The longevities derived from MCL and beach volume are shown for each time interval. Based on the table, it was found that nourishment longevities increased over the years for both coastal indicators. However, the longevities related to beach volume were slightly longer than the longevities related to MCL, except for the time interval (1990 - 1994). By comparing the longevities of the first and last time interval, it can be concluded that the longevities increased by approximately 20% to 25% respectively.

Table 5.6: The representative beach nourishment longevities per time interval along the central Holland coast.

Year	**Representative Beach Nourishment Longevity**	
	MCL	Beach Volume
1990 - 1994	3.25	3.20
1995 - 1999	3.12	3.13
2000 - 2004	3.31	3.98
2005 - 2020	3.77	3.93

Figure 5.1a and Figure 5.1b illustrate grouped boxplots including data of computed beach nourishment longevities. In these grouped boxplots, a distinction was made between longevities derived before and after shoreface nourishments became common practice. This was expressed with the terms: excluding and including shoreface nourishment. The term excluding shoreface nourishment holds when no shoreface nourishment is performed before the completion of beach nourishment. If shoreface nourishment is performed equal or less than 5 years before the completion of beach nourishment, the term including shoreface nourishment holds since this nourishment could positively contribute to the longevity of beach nourishment.

In Figure 5.1, the grouped boxplots show some similarity. The similar features in the boxplots were the increase of upper quartile and interquartile distance when shoreface nourishment was included. In addition, it was also observed that the mean and median of the longevities of both grouped boxplots were larger when beach nourishments were performed after shoreface nourishments became relevant.



(a) MCL

(b) Beach Volume

Figure 5.1: Grouped box plots illustrating the beach nourishment longevities with including or excluding shoreface nourishments. The mean is indicated as an (x), and the median is the horizontal line between the lower and upper quartile.

In Table 5.7, the mean and median values of the longevities are presented for both grouped boxplots. It shows quantitatively how beach nourishment longevities increased after shoreface nourishments became a common practice.

Table 5.7: The representative beach nourishment longevities (mean and median) derived from MCL and beach volume with including or excluding shoreface nourishment.

Shoreface Nourishment	**Mean**		**Median**	
	MCL	Beach Volume	MCL	Beach Volume
Excluding	3.42	3.94	3.07	3.20
Including	5.39	5.65	4.11	4.10

Figure 5.1 and Table 5.7 show clearly the contribution of shoreface nourishments to the increase in beach nourishment longevities. This finding is also supported by Table 5.6 as it can be seen that the longevities increased after shoreface nourishments became relevant in 2000, as stated in Section 3.3.

5.5 Determined Design Aspects

5.5.1 Design Height

The design height is one of the main design aspects of beach nourishment. The method to determine the design height was described in Subsection 4.5.1. To ensure that this method was valid for usage, the documented official design height in the design report was used as a reference. From the 22 considered beach nourishments, only two beach nourishments (Egmond aan Zee in 2011 and Julianadorp in 2016) had a design report. These reports showed that the official design height for both beach nourishments was comparable to the determined design height (+3 metre NAP). In other words, it means that the method to determine the design height was justified, and it could be applied for the rest of the beach nourishments that had no design report.

The design heights of the 22 beach nourishments are presented in Table 5.8. Multiple design height values were determined, and these values were based on various transects where beach nourishments were performed. The average design height was approximately in the range of +3.2 and +3.4 metre NAP. Moreover, the minimum and maximum computed design heights were +1.25 and +6 metre NAP. In the last column of the table, the representative design heights are given per beach nourishment. These values were applied in the MLR model.

In Table 5.8, the results of the confidence assessment are displayed with colours for each determined design height. It appears that only high (green colour) and moderate (yellow colour) levels are shown in the table.

Table 5.8: The results of beach nourishments' design height of various transects.

Coastal Sections	**Locations**	**Beach Nourishments**	**Design Height [m+NAP]**				**Mean**
Noord-Holland	Julianadorp	1992	🟩 3.5	🟩 3.5	🟩 3.2	-	3.40
		1996	🟩 3.25	🟩 2	🟩 1.85	-	2.37
		2003	🟩 3.5	🟩 3.75	🟩 3.8	🟩 3.8	3.71
		2015	🟩 3				3.00
	Callantsoog	1991	🟨 5.5	🟨 5.5	🟨 6	🟨 6	5.75
		1996	🟩 1.75	🟩 1.75	🟨 2	-	1.83
		2004	🟨 3.5	🟨 3.5	🟨 3.5	-	3.50
	Bergen aan Zee	1992	🟨 1.5	🟨 1.5	🟨 1.5	-	1.50
		2005	🟩 2.8	🟩 3.5	🟩 3.15	-	3.15
		2010	🟩 2.9	🟩 3	🟩 2.8	-	2.90
	Egmond aan Zee	1999	🟨 4.5	🟨 4	🟨 4	-	4.17
		2005	🟩 4.5	🟩 4.75	🟨 5.5	🟩 5.5	5.06
		2011	🟩 3				3.00
Rijnland	Bloemendaal aan Zee	1990	🟨 6	🟨 6	🟨 6	-	6.00
		1993	🟨 1	🟨 1.5	🟨 1.25	-	1.25
Delfland	Scheveningen	1975	🟨 0.25	🟨 0.5	🟩 3.5	-	1.42
		1987	🟩 1.25	🟩 4	🟩 4.25	-	3.17
		1991	🟩 4	🟩 4.5	🟩 4.25	-	4.25
		1996	🟩 4	🟩 4	🟩 4	-	4.00
	Ter Heijde	1986	🟩 7.5	🟨 4	🟩 4	-	5.17
		1993	🟨 4.4	🟨 4	🟨 2	-	3.47
		1997	🟨 3	🟨 4	🟨 4	-	3.67

Confidence level	🟩 High	🟨 Moderate	🟥 Low

5.6 Multiple Linear Regression Model

In this section, the measures used to achieve the definitive MLR model are shown. First, the trial and error steps are described. These steps will explain the obstacles that occurred when trying to build the model and which independent variables were left to be used in the definitive model. After describing the trial and errors process, the assessments and results of the definitive model are presented.

5.6.1 Trial and Error Process

In order to build a suitable MLR model, several trial and error steps were taken in advance. These steps were necessary to understand which independent variables should be included. All the models that were used in the trial and error satisfied the regression assumptions described in Subsection 4.6.2. In the section below, the trial and error process will be described to achieve the definitive MLR model.

In the first few trials, various independent variables were included in the MLR model. Besides the general beach nourishment design aspects, other variables were considered, such as execution time and different storm data. The result of the model showed that the R-squared value was significantly low (value in the hundredths decimal place). In addition, it was observed that the adjusted R-squared value differed a lot from the R-squared value. This means that several independent variables were irrelevant to the model and had to be rejected. To find out which independent variables were irrelevant, the results of the t-test were used. The t-test showed that the p-values of almost all independent variables were higher than 0.05. This means that the regression coefficients of these independent variables were insignificant. The most remarkable outcome was that all design aspects were part of these independent variables.

In the next trial, most of the irrelevant independent variables were excluded from the model. Only variables that were needed to answer the research questions were taken into account. The following independent variables were included: design aspects, summer or storm season and beach nourishment before a storm. Using these variables showed a significantly higher R-squared value in the model than in the first trial. However, the difference between adjusted R-squared and R-squared became larger. Besides, the outcome of the t-test showed that the regression coefficients of the storm variables and the volume design aspect were still insignificant. Nevertheless, the regression coefficients of the design height and length became significant.

The latter outcome was encouraging as the design aspects were still of relevance for the model when the right independent variables were chosen. Therefore, it was decided to run the MLR model once again with only the design aspects values (design height, design length and design volume per metre) as independent variables. Using these variables resulted in the definitive MLR model, where all the regression coefficients of the design aspects were significant.

5.6.2 Definitive Assessment of Regression Assumptions

In Subsection 4.6.2, it was stated that the MLR model needs to satisfy a few key assumptions. The assessments of the definitive MLR model’s assumptions are described below.

Linear Relationship Between Variables

The relation between each design aspect (independent variable) and the longevity (dependent variable) are presented in Figure 5.2. The relationship is shown with a scatter plot, in which the dependent and independent variables showed a moderate linear relationship instead of a curvilinear relationship. Therefore, it can be concluded that all the variables in the MLR model satisfied the assumption of a linear relationship.

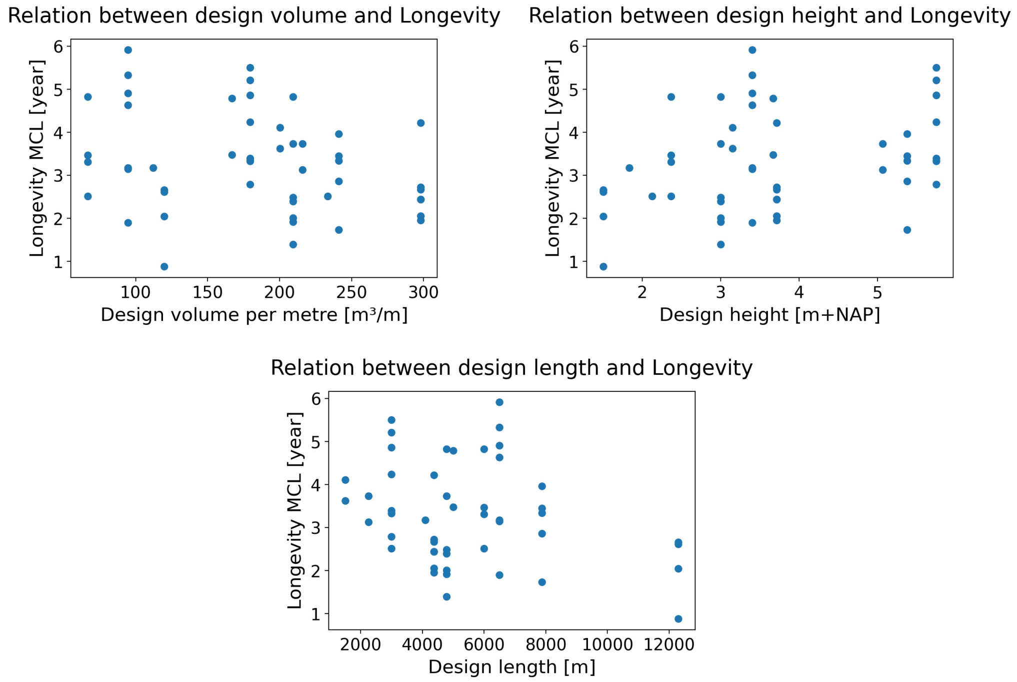
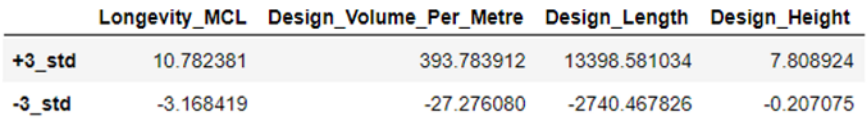


Figure 5.2: The relationship between dependent variable (longevity MCL) and each independent variable (design volume per metre, design height, and design length).

No Outliers

The cut-off values to identify the outliers for each variable is presented in Figure 5.3. Based on the cut-off values, four observations consisted of an outlier. The removal of the outliers resulted in the definitive dataset with only 49 observations.



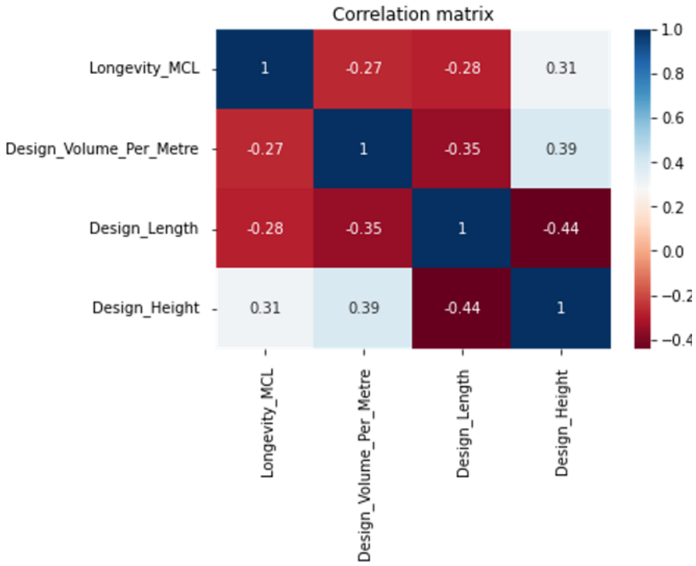
	Longevity_MCL	Design_Volume_Per_Metre	Design_Length	Design_Height
+3_std	10.782381	393.783912	13398.581034	7.808924
-3_std	-3.168419	-27.276080	-2740.467826	-0.207075

Figure 5.3: A concise overview of the design aspects' cut-off values. The cut-off values are based on three times the standard deviation from the mean.

No Multicollinearity

A correlation matrix is illustrated in Figure 5.4. This matrix displays the correlation coefficients between the variables in the model. From the correlation matrix, it can be observed that none of the variables had a mutual correlation value of 0.8 or higher. These results revealed that this definitive model might not have highly correlated variables.

In Figure 5.5, the values of VIFs are presented to ensure that none of the variables is highly correlated. It is noticed in the table that none of the variables had a VIFs value of 5 or higher. Hence, it can be concluded with more certainty that the independent variables were not highly correlated. Thus, this definitive model had no multicollinearity.



	Longevity_MCL	Design_Volume_Per_Metre	Design_Length	Design_Height
Longevity_MCL	1	-0.27	-0.28	0.31
Design_Volume_Per_Metre	-0.27	1	-0.35	0.39
Design_Length	-0.28	-0.35	1	-0.44
Design_Height	0.31	0.39	-0.44	1

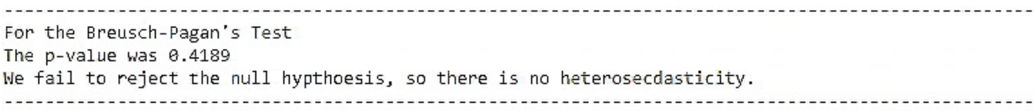
Figure 5.4: A correlation matrix showing the correlation coefficients between the included variables (longevity MCL, design volume per metre, design height, and design length). None of the correlation coefficients is 0.8 or higher.

```
--------------------------------------------------------------------------------------------
Longevity_MCL              1.511639
Design_Volume_Per_Metre    1.645195
Design_Length              1.431851
Design_Height              1.576987
dtype: float64
--------------------------------------------------------------------------------------------
```

Figure 5.5: The numerical values of the variance inflation factors (VIFs) to test multicollinearity in the model. The VIFs values have proved that none of the variables is highly correlated.

Homoscedasticity

The outcome of the Breusch-Pagan test is presented in Figure 5.6. This hypothesis test examines whether the model is homoscedastic. The result of the Breusch-Pagan test showed that the p-value is 0.4189, which is larger than 0.05. This means that the model was not heteroscedastic, and therefore the assumption of homoscedasticity was valid in this definitive model.



```
--------------------------------------------------------------------------------------------
For the Breusch-Pagan's Test
The p-value was 0.4189
We fail to reject the null hypthoesis, so there is no heterosecdasticity.
--------------------------------------------------------------------------------------------
```

Figure 5.6: The result of the Breusch-Pagan test to examine homoscedasticity in the MLR model. The Breusch-Pagan test shows that the model is homoscedastic.

No Autocorrelation

In Figure 5.7, it is proved that no autocorrelation is present in the model. It can be seen in the correlogram that data points were randomly scattered. This was a feature of no autocorrelation. Therefore, it can be concluded that this definitive model had no autocorrelation.

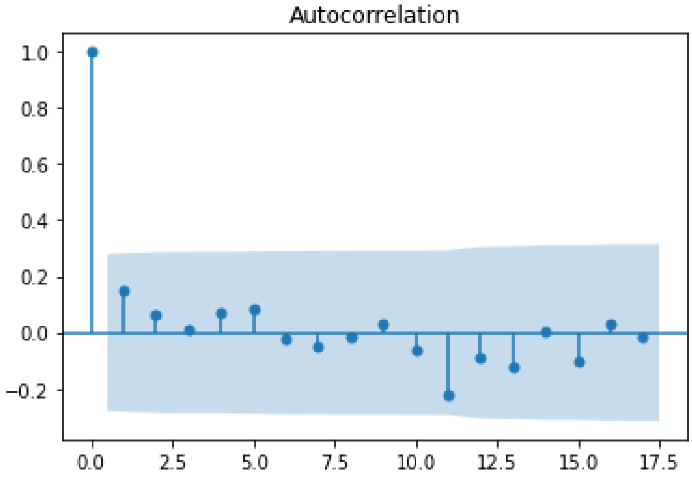


Figure 5.7: A correlogram to examine autocorrelation in the MLR model. The correlogram displays features of no autocorrelation.

Normally Distributed Residuals

A Q-Q plot is presented in Figure 5.8. This plot is useful to test whether residuals are normally distributed. The Q-Q plot shows that data points were plotted along a straight line. This feature was essential because this indicated the normal distribution of the residuals in this definitive model.

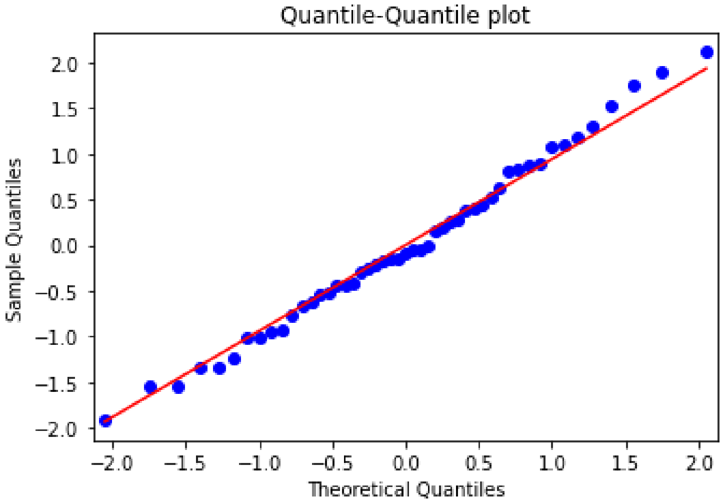


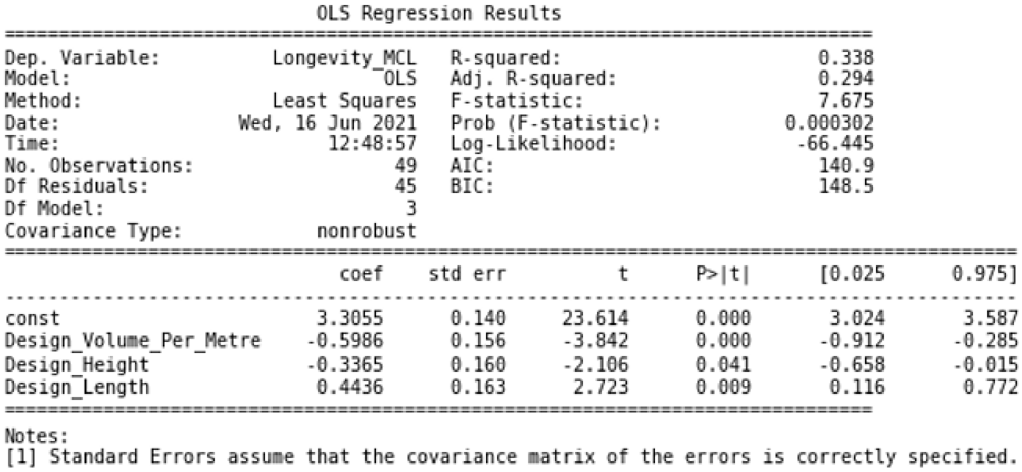
Figure 5.8: A quantile-quantile (Q-Q) plot to examine residuals in the MLR model. The Q-Q plot displays features of normally distributed residuals.

Conclusion

Based on all the results of the assessments, one can conclude that the definitive model fulfilled all the assumptions (linear relationship between variables, no outliers, no multicollinearity, homoscedasticity, no autocorrelation, and normally distributed residuals).

5.6.3 Definitive MLR Model Summary

The results of the definitive MLR model are summarised in Figure 5.9. The top left panel of the summary shows some general information about the model. For example, the dependent variable is the beach nourishment longevity derived from MCL, the used method is OLS, and the total used observation is 49. In the top right panel of the summary, some statistical tests and measures are shown. For instance, the essential R-squared value and the F-statistic.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:          Longevity_MCL   R-squared:                       0.338
Model:                            OLS   Adj. R-squared:                  0.294
Method:                 Least Squares   F-statistic:                     7.675
Date:                Wed, 16 Jun 2021   Prob (F-statistic):           0.000302
Time:                        12:48:57   Log-Likelihood:                -66.445
No. Observations:                  49   AIC:                             140.9
Df Residuals:                      45   BIC:                             148.5
Df Model:                           3
Covariance Type:            nonrobust
===========================================================================================
                              coef    std err          t      P>|t|      [0.025      0.975]
-------------------------------------------------------------------------------------------
const                       3.3055      0.140     23.614      0.000       3.024       3.587
Design_Volume_Per_Metre    -0.5986      0.156     -3.842      0.000      -0.912      -0.285
Design_Height              -0.3365      0.160     -2.106      0.041      -0.658      -0.015
Design_Length               0.4436      0.163      2.723      0.009       0.116       0.772
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
```

Figure 5.9: The summary of the definitive multiple linear regression model.

The R-squared value of this model was 0.338. Further, it was observed that the adjusted R-squared only differs 0.044 from the R-squared value. This slight difference indicated that all the included independent variables were relevant.

The following essential test was the F-test. The probability value of the F-test was 3.02E-4, which was considerably smaller than the significance level of 0.05. As a result, the null hypothesis was rejected. Supporting the alternative hypothesis implied the existence of a linear relationship between the dependent and independent variables.

In the middle part of the summary, the coefficients and the t-test for each independent variable are indicated. Based on the t-test, all p-values of the t-statistic were smaller than the significance level of 0.05. These p-values suggested that the null hypothesis could be rejected for each independent variable. Supporting the alternative hypothesis for all three independent variables implied that these variables' regression coefficients were significant.

Since the regression coefficients were tested significantly, the coefficient could be interpreted with confidence. The first regression coefficient was the intercept (3.3055). The following values were regression coefficients of the independent variables. The variable design volume per metre had the largest coefficient magnitude, and the variable design height the smallest. Furthermore, the variables design volume per metre and design height showed a negative sign, while the variable design length had a positive sign. The negative regression coefficients implied that the larger design volume per metre and a higher design height elevation result in shorter longevity. The positive regression coefficient suggested that a longer beach length results in longer longevity.

After some tests, it appeared that the sign of the variable design volume per metre was fluctuating. This outcome was found out by running the MLR model a hundred times with omitting randomly two observations. The model summaries showed that approximately 40% of these regression coefficients had a positive sign, whereas 60% consisted of a negative sign. This was a remarkable result since the other variables had a fixed sign.

6 Discussions

This chapter contains a critical interpretation and evaluation of the research results from the previous chapter. First of all, the reliability of the model results is discussed. Secondly, the representation of the computed longevities is argued. The third section is about the factors that result in the increase of beach nourishment longevities over time. In the fourth section, the sign interpretation of the regression coefficients is discussed. In the fifth section, the added value of the multiple linear regression is described. Finally, the relevance of storm variables is discussed.

6.1 Reliability of the Model Results

In this section, the reliability of the model results will be discussed. First, the constraints of the model will be presented and afterwards the limitations of the method to compute beach nourishment longevity.

6.1.1 Number of Observations

In total 49 adequate/available observations have been applied in the MLR model. This amount of observations is limited. It is desired to include more observations since it increases the probability of having useful information to analyse data and improve the model's accuracy. Despite a relatively low number of observations, it is expected to be adequate to analyse the general relationship between beach nourishment longevity and the three design aspects along the central Holland coast.

6.1.2 R-squared

In Subsection 5.6.3, the summary of the definitive MLR model is presented. A remarkable statistical measure in the summary is the R-squared value. It is noticed that the R-squared value (0.337) is relatively low for a regression model. This is not surprising as this model deals with variables that are affected by nature-based physical processes. Due to the low R-squared value, the magnitude of the regression coefficients can not be interpreted with confidence to explain the expected change between dependent and independent variables. Nevertheless, a low R-squared value does not necessarily mean that the model is pointless. If the independent variables are statistically significant, conclusions about the relationship between the dependent and independent variables can still be drawn. The definitive MLR model has proved with p-values that the regression coefficients are statistically significant. Therefore, the relationship between beach nourishment longevity and design aspects along the central Holland coast can be analysed using the sign of the regression coefficients. In addition, a high R-squared value is essential for making predictions, but that is not the aim of this study. The aim of this study is to understand the relationship between multiple design aspects and the longevity of beach nourishment.

6.1.3 Limitations of the Longevity Method

As explained in Subsection 4.1.2, the coastal indicators in the dataset are derived from the JARKUS data. Imprecision in the data can therefore affect the coastal indicator dataset. In Subsection 4.1.2, it was mentioned that the JARKUS data is measured with two different techniques to obtain the cross-shore profiles. The data shows that the two different measurement techniques were not performed simultaneously but often a few months after the other. As a result, the seasonal variation could occur in the measured coastal profiles, as described in 2.3. Besides, interpolations are needed to construct the complete cross-sectional profiles. All in all, it is expected that the measured cross-shore profiles can slightly differ from the actual profiles due to the seasonal variation in the measured cross-shore profiles and interpolation. Consequently, uncertainty appears in the coastal indicator data, which will slightly lead to under- or overestimation in the results of the computed longevities.

The described method to compute beach nourishment longevity, in Subsection 4.3.2, has certain limitations and uncertainties. The first limitation is that longevity is derived with a linear regression instead of an exponential regression. An exponential regression should fit the coastal indicator data better since the erosion rate after beach nourishment decays exponentially (Dean and Yoo, 1992). Despite that the exponential regression is favourable, it is decided to choose a linear regression since not every longevity can be derived from exponential regression as this requires a certain amount of coastal indicator data. As a result, the computed beach nourishment longevities with a linear regression can slightly differ from the actual longevity.

Another limitation is that beach nourishment longevities are not derived with coastal indicator data shortly before and after beach nourishment. This specific data is not included in the general JARKUS dataset because there is no demand for it. One of the main purposes of this dataset is to verify whether the MKL exceeds the BKL. In order to do this, additional data is not necessary. Nevertheless, in this study, these two data points are essential since they can affect the slope of the regression line to a certain extent and thus the precision of the longevity. The missing data can be derived from the cross-shore profiles obtained from the contractor's pre and post dredge surveys. However, it will take some time to collect this data. With the limited time available, it was decided not to collect this specific data.

In Figure 6.1, an example is given how the two excluded coastal indicator data can affect the regression line and the longevity of beach nourishment. The figure shows green and red dashed lines after beach nourishment was carried out. The red dashed line is the regression line that has been used in this study, and the green dashed line is the regression line that is supposed to be used. This line has included the coastal indicator data shortly after beach nourishment was carried out. In the figure, it can be observed that the green dashed line is steeper than the red dashed line. To determine the longevity with the regression line, the available coastal data shortly before beach nourishment was used as a reference. Based on this information, the longevity can be depicted with a distance arrow. As can be seen in the figure, the red distance arrow (computed beach nourishment longevity) is slightly longer than the green distance arrow (supposed beach nourishment longevity). This outcome is valid for all beach nourishment. Consequently, this means that all the computed beach nourishment longevities in this study are slightly overestimated compared with the longevities that are computed with the supposed regression lines. This new finding will not have severe consequences for the relationship analysis between longevity and design aspects since it is valid for all the determined nourishment longevities.

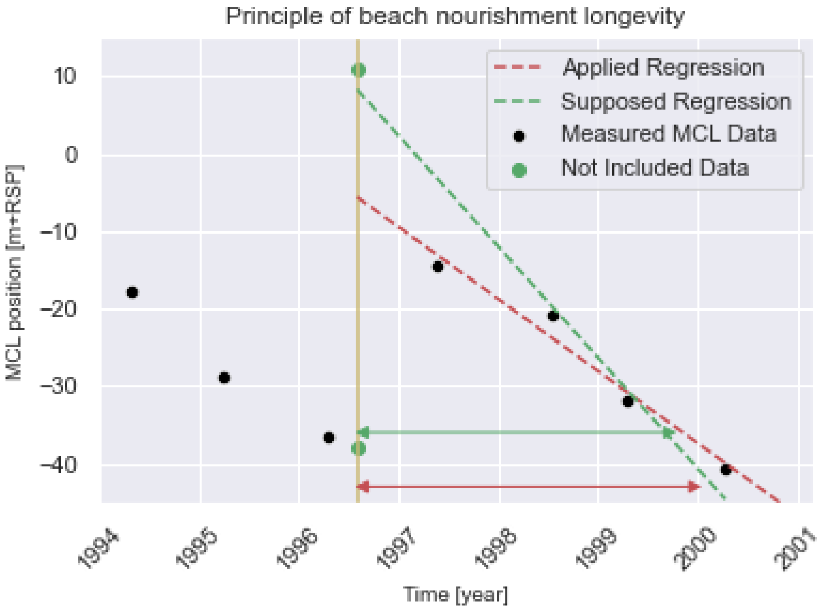


Figure 6.1: A graph that depicts how the regression line can be affected when the coastal indicator data shortly before and after a performed beach nourishment are not included. As can be seen, the supposed beach nourishment longevity (green distance arrow) is shorter than the computed beach nourishment longevity (red distance arrow). The following aspects are presented: the coastal indicator data (black dots), the completion date of beach nourishment (yellow vertical line), not included coastal indicator data (green dots), applied regression line (red dashed line), and supposed regression line (green dashed line).

The next limitation of the longevity method is related to nourishment data. As stated in the previous section, the exact completion day of the beach nourishment was not available. This day is essential as beach nourishment longevity is computed by subtracting the completion date of beach nourishment with the date of no beach nourishment effect. As the completion day is unknown, it was decided in this study that the nourishments were completed on the first day of the month to compute longevity. However, due to this approach, the computed beach nourishment longevities impose a supplementary uncertainty with a maximum deviation of one month.

The final uncertainty in the method is a result of the natural variability in the beach topography. This natural variability of the beach affects the coastal indicator data and results in occasionally inadequate regression lines for computing nourishment longevities. In Subsection 4.3.2, it was described that a regression line with a negative slope is needed to compute the beach nourishment longevity. In order to create an ideal regression line, the coastal indicator data should decay over the years. However, according to the available data, this is not always the case. At some transects, the coastal indicator data increase through the years after beach nourishment is carried out. In Subsection 5.2.2, it was stated that even after modifying the coastal indicator data (beach volume), the increase of the coastal indicator data after beach nourishment still occurs. The assumption that cyclic movement of the sandbars is the main reason that results in this effect is therefore incorrect. Apparently, other natural phenomena can also cause extra volume in the calculation zone and increase the coastal indicator values after beach nourishment is carried out.

A possible natural phenomenon leading to this additional volume is sediment from dune erosion during a storm event. The storm surges reach the front of the dunes and cause erosion. The eroded sediments move to the offshore direction and settle on the beach (Vellinga, 1982). The eroded sediments that are settled on the beach might be located in the calculation zone of the coastal indicator. However, based on the JARKUS cross-shore profiles, no evident dune erosion are visible that might increase beach volume. Another possible explanation is the longshore transport phenomenon. As stated in Section 2.3, this transport is an outcome of the longshore current induced by oblique waves and tides. The longshore currents convey and distribute the sediment along the beach. The volume increase may result from the sediment deposition on the beach due to longshore sediment transport.

Different natural phenomena can increase beach volume, even after beach nourishment is carried out. The additional volume due to longshore transport or dune erosion can not be prevented by simply adjusting the boundaries of the calculation zone, just as in the case of the sandbars. These natural phenomena can still influence the slope of the regression line and affect nourishment longevity. In a most unfavourable circumstance, a positive regression line is plotted, and no longevity can be computed.

In conclusion, several limitations can affect the precision of the computed nourishment longevities. In general, it is estimated that the longevity of individual nourishments is over- or underestimated by a maximum of a few months due to these limitations. However, this is less than the variability in longevities that occurs in the dataset. Furthermore, it is expected that the random errors due to the limitations will cancel each other out. Therefore, it is believed that the results are not much affected by the limitations.

6.2 Alongshore Variability of Beach Nourishment Longevity

In Table 5.5, the average beach nourishment longevities per location are given. However, not every value in this table can be interpreted as the representative average longevity. The median longevity value per location (e.g. Bloemendaal aan Zee and Ter Heijde, see Appendix A) is computed with only one beach nourishment. Therefore, this value does not properly represent the average beach nourishment longevity of the location. Furthermore, the tables in Appendix A show that some of the determined median longevity values of beach nourishments depend on only one transect due to the confidence level condition. Thus, these values barely represent the median longevity values of beach nourishments. As a result, this will affect the representation of beach nourishment longevities at some locations (e.g. Scheveningen and Egmond aan Zee, see Appendix A).

In Table 6.1, the representation level of the average longevity is displayed for each location. The representation level consists of three categories: high, moderate and low.

The explanation of the three categories are listed below:

- **High representation level**: the beach nourishment longevity is computed with more than three transects, and the average nourishment longevity per location is determined with more than two beach nourishments.
- **Moderate representation level**: the beach nourishment longevity is computed with at least two or three transects, and/or the average nourishment longevity per location is computed with only two beach nourishments.
- **Low representation level**: the beach nourishment is computed with only one transect, and/or the average nourishment longevity per location is computed with only one beach nourishment.

Table 6.1: The representation level for each computed median value of beach nourishment longevities per location.

Coastal Section	**Location**	**Transect**	**Average longevity per location**	
			MKL	Beach Volume
Noord-Holland	Julianadorp	170 - 528	🟩 2.94	🟨 3.21
	Callantsoog	1137 - 1340	🟨 3.18	🟨 3.21
	Bergen aan Zee	3175 - 3275	🟥 2.62	🟥 3.14
	Egmond aan Zee	3725 - 3800	🟨 3.77	🟥 3.92
Rijnland	Bloemendaal aan Zee	6175 - 6300	🟥 1.68	🟥 5.32
Delfland	Scheveningen	9925 - 10075	🟥 3.13	🟨 3.47
	Ter Heijde	11034 - 11244	🟨 3.75	🟥 3.21

Representation level	🟩 High	🟨 Moderate	🟥 Low

Overall, the actual purpose of Table 6.1 has not been served. The alongshore variability in nourishment longevities cannot be determined, mainly due to the limited amount of representative nourishments per location. However, it is noticed that longevities along the central Holland coast is typically 3-3.5 years.

6.3 Longevity Development through Time

The computed beach nourishment longevities in this study showed that the longevities have increased through the years in the central Holland coast (see Table 5.6). The increase was noticeable after 1999 when shoreface nourishment became relevant. The positive effect of shoreface nourishment was also depicted in Figure 5.1. Based on these findings, there is a tendency to assume that shoreface nourishment has a favourable effect on beach nourishment longevity. However, this positive effect can also be associated with the significant increase of the nourishment volume through the years (Ministry of Infrastructure and Water Management, 2015 and Van der Spek et al., 2015). Therefore, it is difficult to conclude which of the two events contribute to a longer beach nourishment longevity.

Over the years, different researchers have argued whether shoreface nourishment contributes to the beach width or not. For instance, Van Duin et al. (2004) and Ojeda et al. (2008) have reported that the supplied sediments of shoreface nourishment in Noordwijk and Egmond aan Zee were eroded before it could reach the beach. While Grunnet and Ruessink (2005) have made an opposite statement for the location Terschelling. According to Ojeda et al. (2008), the different statements are probably due to the location of the nourishment on the cross-shore profile. Besides practical experience, a process-based model (DELFT3D) is also used to understand shoreface nourishment. According to Walstra et al. (2004) shoreface nourishment could have a positive influence on the sand volume in the inner bar regions and intertidal beach area. In addition, they also reported that the volume of shoreface nourishment has a relatively large effect on how the MKL-position will move.

In summary, the computed beach nourishment longevities show that they have increased through the years. However, even with available studies, no clear conclusion can be drawn whether this effect is created by shoreface nourishments, an increase of nourishment volumes through the years, or the combination of both. Nevertheless, based on Figure 5.1 and Table 5.6, a cautious assumption can be made in general that shoreface nourishments along the central Holland coast may positively contribute to the beach nourishment longevity.

6.4 Sign Interpretation of the Regression Coefficients

In this section, the interpretations of the most important results from the MLR model are discussed.

6.4.1 Regression Coefficients

The signs of the regression coefficients are an essential result of this study. In the model summary, four regression coefficients are provided. These signs reveal the relationship between beach nourishment longevity and the design aspects. To interpret the regression coefficients correctly, the signs of the regression coefficients are substantiated with literature.

Intercept

The first positive regression coefficient is the intercept. This value has no physical meaning. The latter statement is not extraordinary because if the intercept has a physical meaning, it will suggest that beach nourishment longevity is approximately three years without any design aspects, which is impossible.

Design Volume per Metre

The next regression coefficient is for the independent variable design volume per metre. In Subsection 5.6.3, it was stated that the regression coefficient was fluctuating between a positive and negative sign after numerous reruns of the MLR model. Three possible situations can be interpreted due to the variation in sign. The first situation (positive sign) suggests that a larger volume per metre results in longer longevity. The second situation (value close to zero) suggests that there is a weak or no relationship between volume per metre and longevity. The third situation (negative sign) suggests that a larger volume per metre results in shorter longevity.

According to the reruns of the model, a slight preference for a negative sign is indicated in the MLR model. This is remarkable since it is expected intuitively that a larger volume will result in longer longevity as a larger volume may enhance the compensation for coastal erosion. The intuitive expectation is in accordance with the study of Gijsman et al. (2018). They reported for their study area (Sylt, Germany) that the design volume per metre has a positive regression coefficient. However, the determined regression coefficient by Gijsman et al. (2018) does not suggest that it is also applicable for the central Holland coast because the morpho- and hydrodynamic conditions between the central Holland coast and Sylt are not equivalent. Moreover, it is expected that the alongshore coastline characteristic of Sylt is more uniform than the central Holland coast due to a smaller research area. Therefore, it is most unlikely to rule out the opposite regression coefficient sign based on the outcome of Gijsman et al. (2018).

A possible reason that the model shows a preference for a negative sign in this study is due to the erosional hot spots (EHS) phenomenon. EHS is an area with a high erosion rate as compared to the adjacent beach or to the expected behaviour of the beach (Kraus and Galgano, 2001). To cope with the higher erosion rate in an EHS area, more nourishment volume needs to be applied. This can explain why the MLR model provides a negative sign. The theory of EHS is reasonable in this study since all the selected locations are frequently nourished to mitigate coastal erosion.

Overall, based on the fluctuating regression coefficient of the independent variable design volume per metre, it can be concluded that the relationship between design volume per metre and beach nourishment longevity is not certain. The fluctuating sign can represent a positive, negative or not correlated relationship. As a result, no certain conclusion can be drawn of which design volume per metre is ideal for extending the longevity of the beach.

Design Height

The independent variable design height has a negative regression coefficient. This means that a higher design height elevation will result in a shorter beach nourishment longevity. This outcome is surprising because it is expected intuitively that a higher design height reduces the chance of wave set-up reaching a larger area of the beach. Gijsman et al. (2018) have revealed in their study area that the design height has a positive regression coefficient. This outcome is in line with the intuitive expectation. Although, just as in the case of design volume per metre, the determined sign in their study does not indicate it is also valid for this study.

A possible reason for the negative regression coefficient of the design height in this study might be related to the beach scarp phenomenon, which occurs shortly after the implementation of beach nourishment (van Bemmelen et al., 2020). According to van

Bemmelen et al. (2020), the formation of the beach scarps is a gradual process in which the beach profile steepens until the first slumping occurs. In that study, it was mentioned that scarps are often formed during the summer storm conditions, and destruction occurs during the winter storm condition. Presumably, the destructed beach scarp moves in the offshore direction during a storm, which results in beach erosion. Furthermore, they reported that beach scarps are more likely to occur on the nourished sites with an initial steep beach profile and a high platform elevation.

The latter finding reveals a tendency to assume that a gentle initial beach slope and a lower design height may reduce the formation of beach scarps and therefore possibly coastal erosion. Besides, an increase in design height might result in a steeper and out of equilibrium beach profile. A steep beach profile dissipates less wave energy than a gentle beach profile (Dette and Raudkivi, 1995). Consequently, a higher erosion rate is expected. The theory about beach scarps is in accordance with the model's suggestion. Hence, it is believed that a lower elevation of the design height may result in a longer beach nourishment longevity and vice versa.

Design Length

For the independent variable design length, the sign of the regression coefficient is positive. This suggests that a longer design length leads to a longer beach nourishment longevity. The positive regression coefficient is equivalent to the sign determined by Gijsman et al. (2018).

Different researches support the sign of this regression coefficient. According to Van Rijn (2011), the length of beach nourishment needs to be at least 3 kilometres to mitigate the erosion at both alongshore ends due to the dispersion effect under normal wave attack. By making longer beach nourishment, the decay of total nourishment volume may be reduced. In 2017, Drønen et al. have proved that a longer beach nourishment length results in a slower relative volume decay by using a morphological 2DH model.

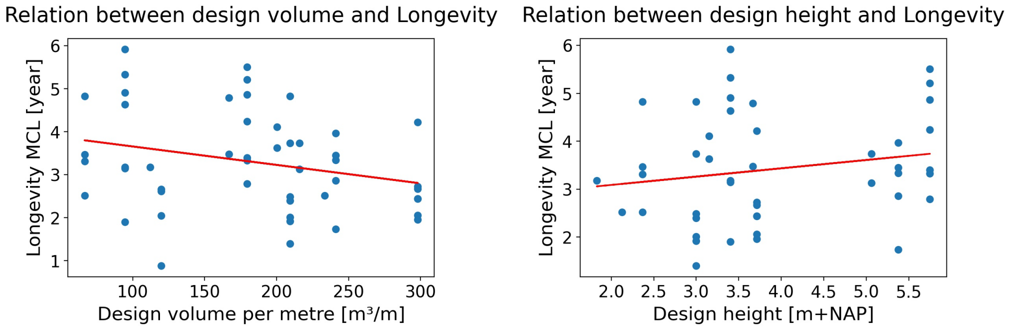
Based on these research findings, it is believed that the sign of the regression coefficient is correct. Therefore, a longer design length will result in a longer beach nourishment longevity and vice versa.

6.5 Added Value of Multiple Linear Regression Model

In this study, the observations included in the MLR model are relatively low. Nevertheless, it is expected that the available observations are sufficient to obtain a first insight into the relationship between beach nourishment longevity and the design aspects on a regional scale. Further, it is pointed out that a model with a relatively low R-squared value is still adequate for the analysis since the sign of the regression coefficients shows the relationship between the variables. In the model summary, some of the regression coefficients have a remarkable sign. However, based on the literature, these signs can be substantiated. Therefore, it is believed that the interpretation of most regression coefficients is appropriate. Consequently, the interpretation of regression coefficients from the

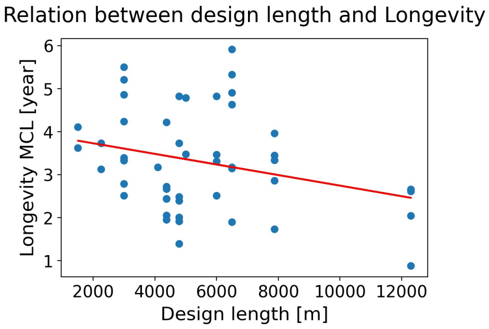
MLR model suggests that a lower design height elevation and a longer design length will result in a longer beach nourishment longevity. For design volume per metre, no specific design can be proposed to extend the beach nourishment longevity. This is due to the fluctuating regression coefficient sign.

Three univariable linear regression subplots are depicted in Figure 6.2. The univariable linear regression can be used to study the relationship between two variables. In each subplot, the best fit line is illustrated. These regression lines explain the relationship between the dependent variable and a single independent variable. The variables that are used in these subplots are assessed with a high confidence level. In each subplot, the corresponding regression coefficient of the line is given. It can be observed that the variables design volume per metre and design length have a negative regression coefficient, while the variable design height has a positive regression coefficient.



(a) Regression coefficient: negative

(b) Regression coefficient: positive



(c) Regression coefficient: negative

Figure 6.2: Three univariable linear regression subplots are depicted. The dependent variable is longevity MKL, and the independent variables are design volume per metre, design height, and design length.

The signs of the regression coefficients are remarkable since the independent variables design height and design length have an opposite sign compared to the signs provided by the multiple linear regression. The only independent variable that may have the same sign is the variable design volume per metre. In this case, the univariable linear regression suggests that larger design volume per metre and longer design length will result in shorter longevity, while a higher design height elevation results in longer longevity.

A univariable linear regression can only be effectively interpreted when other independent variables affecting the dependent variable are uncorrelated with the applied independent variable. This is unrealistic since most of the independent variables are related to the design of beach nourishment. Therefore, individual regression coefficients from a univariable linear regression are not sufficient to explain the beach nourishment longevity. Consequently, multiple linear regression is a more suitable approach to understand the relationship between longevity and multiple design aspects.

6.6 Storm Variables

In Subsection 5.6.1, it was stated that the storm variables were not included in the definitive MLR model. The variables were omitted because the storm variables were insignificant according to statistical measures. Although, the model revealed that the storm variables are insignificant, it can not be ruled out that storms do not have any relationship with beach nourishment longevity. These storm variables could be significant in the model if it is combined with appropriate variables. However, these variables are obscure.

Although no conclusion can be drawn in this study about the relationship between storm and beach nourishment longevity with the MLR model, many researchers have proposed through the years that storm does have a certain effect on beach nourishment. In 1989, Möller and Swart have reported that beach nourishment carried out during a storm has a high erosion rate. Verhagen (1992) has addressed that heavy storm event results in partial deposition of nourished sediment outside the control-volume. In 2003, Aarninkhof et al. have proved with video monitoring in Egmond aan Zee that storm sequences in 1999 have resulted in a significant coastal retreat despite introducing nourishment to mitigate local beach erosion. The storm had such an impact on the beach that the coastline was still not recovered even by the end of June 2000.

All in all, these findings show that storm has a damaging effect on beach nourishment, and therefore it is implausible to surmise that storm has no relationship with beach nourishment longevity.

6.7 Other Design Aspects of Beach Nourishment

In this study, only the design aspects volume per metre, height and length are taken into account in the MLR model. The definitive model revealed that these design aspects are of primary interest. But there are plenty of other design aspects that can be interesting as well, such as berm width, slope, and sediment size (Van Rijn, 2011 and Dean, 2003). These design aspects may also influence the beach nourishment longevity.

Based on trial and error experiences with the MLR model, adding new design aspects such as berm width, slope and sediment size; can change the new and former design aspects' relevancy in the MLR model. However, it is believed that adding these new design aspects in the model will not influence the relevancy of the former design aspects. The reason is that the new design aspects are related to the former design aspects. Moreover, the definitive model showed that the former design aspects are relevant. Further, it is expected that the newly added design aspects will also be relevant since the new and former design aspects are related to each other. However, to confirm this assumption, the MLR model must run again with all the design aspects. The model summary will show whether the former and new design aspects are relevant and statistically significant.

In conclusion, the definitive MLR model in this study revealed that the design aspects volume per metre, height and length are definitely of main interest. Nevertheless, various literature has reported that other design aspects can be interesting as well. Therefore, to conclude that volume per metre, height and length are the only primary design aspects that affect beach nourishment longevity is implausible.

7 Conclusions

This study attempted to understand the relationship between design aspects and the longevity of beach nourishment. The findings of this research will be referred to the formulated research questions in Chapter 1.

7.1 Main Question

Which design aspects are primarily affecting the beach nourishment longevity along the central Holland coast?

The result of the definitive MLR regression model indicated with statistical tests and measures that the design aspects volume per metre, height and length are essential for explaining the behaviour of longevity in the MLR model. The slight difference between the adjusted R-squared and R-squared (0.044) showed that the included design aspects are relevant. Moreover, the tested p-values of the t-statistic ($p < 0.05$) proved that the regression coefficients of these design aspects are all statistically significant for interpretation. However, from the three design aspects, it can only be concluded that design height and length affect the beach nourishment longevity along the central Holland coast. For the design aspect design volume per metre, no certain conclusion can be drawn due to the fluctuating sign of the regression coefficient. Furthermore, it can not be concluded with the MLR model that these three design aspects are the only design aspects of primary interest. Other design aspects can also be interesting and essential in the MLR model.

7.2 Sub Questions

What are the longevities of beach nourishments along the central Holland coast?

The inventory of all the labelled confidence levels showed that most of the longevities were labelled with a moderate confidence level. This confidence level resulted in difficulties in computing the representative beach nourishment longevities and thus the average longevity per location. Consequently, no conclusion can be drawn on how the longevities differ between the locations. Nevertheless, the computed longevities show that common beach nourishment longevity along the central Holland coast ranges between 3 and 3.5 years.

To what extent has the longevity of beach nourishments changed over time?

This study showed that the beach nourishment longevities generally increased by approximately 20% to 25% between 1990 and now when comparing the first and last time interval. In addition, it was revealed that a distinct increase in longevity was observed after 1999. This was also the moment when shoreface nourishments became a common practice. Based on these results, there is a tendency to assume that shoreface nourishments may increase the longevities of beach nourishments. Nevertheless, this is just an assumption since the increase of total nourishment volume through the years can also lead to this effect. Combining both shoreface nourishments and an increase of total nourishment volume along the coast is also an option. Therefore, the results of this study only show that the longevities of beach nourishments have increased through the years. However, no conclusion can be drawn on which factors contribute to the increase in longevities.

To what extent do nourishment design aspects (volume per metre, length and height) have an influence on the longevity of beach nourishments?

The definitive MLR model revealed that the sign of design volume per metre is fluctuating. This indicates that the design aspect design volume per metre can positively, negatively or even not correlate with the nourishment longevity. Consequently, no clear conclusion can be drawn on how the design volume per metre will influence the longevity of beach nourishment.

For design height and design length, the signs of the regression coefficients are fixed. Therefore, the interpretation of how these design aspects can influence nourishment longevity is more straightforward. The negative regression coefficient of design height implies that a lower design height elevation will result in longer longevity of beach nourishment. While the positive regression coefficient of the design length indicates that a longer design length results in longer longevity of beach nourishment.

All in all, it can be concluded that the MLR model in this study has identified the influence of design length and height on nourishment longevity. However, it is impossible to confirm the influence of design volume per metre on the nourishment longevity. Even though the influence of one design aspect is not clear, the signs of these regression coefficients provide a first qualitative insight into the relationship between design aspects and beach nourishment longevity of the central Holland coast.

To what extent have beach nourishments effect on longevity that are applied shortly before a storm?

In the MLR model, several trial and error steps were taken in advance to find out which design aspects were significant for the analysis. Based on the trial and error results, it is remarked that storm variables are negligible in the MLR model. Therefore, it is impossible to determine how the nourishment longevity will be affected when beach nourishment is applied shortly before a storm. Although the model shows that the storms are negligible, it does not imply that storms do not affect the longevity of beach nourishments. It is believed that the storm variables can be significant in the MLR model if the right variables are included.

8 Recommendations

This thesis highlighted how several design aspects could affect the longevities of beach nourishments along the central Holland coast. These new findings can be useful for further research. The recommendations for the follow-up studies are listed below in the following sections.

8.1 Collect Additional Data

During the study, it was noticed that several design aspects were not available or were not consistently added to the nourishment dataset. The missing data of the design aspects can be obtained from the official design documents of individual beach nourishment. Although, applying this approach to the entire central Holland coast is very time-consuming. Therefore, to obtain this data more convenient and immediate in future studies, it is strongly recommended to add the design aspects information of future nourishments (e.g. height, berm width, slope, and grain size) into the nourishment dataset.

8.2 Further Research

This study showed that multiple linear regression is a valid method to analyse the relationship between design aspects and longevity of beach nourishment. Thus, it is recommended for this type of study to apply MLR in the future.

In further research, it is recommended to use the cross-shore profiles just before and after beach nourishments. The additional cross-shore profiles can be obtained from pre and post dredge surveys of the contractor. The missing coastal indicator data just before and after beach nourishments can be derived with these cross-shore profiles. The data can improve the precision of the regression line to compute beach nourishment longevity.

According to the MLR model, the design aspect design volume per metre showed a fluctuating regression coefficient sign. This is remarkable since the signs of the other design aspects were fixed. As a result, no certain conclusion can be drawn on how this design aspect can influence longevity. Therefore, it is recommended to investigate the behaviour behind the fluctuation of the sign.

The MLR model revealed that the design aspects design length and design height were definitely affecting the nourishment longevity. Nevertheless, there are other design aspects (e.g., berm width, slope, and sediment size) that can be essential as well. In further studies, it is recommended to test whether other potential design aspects are of relevance.

In addition, it is recommended to determine the factors that lead to the irrelevance of storm variables in the MLR model. Including storm variables in the MLR model is still interesting as it can explain how the longevity of beach nourishment can be affected when beach nourishment is applied just before a storm. Understanding this effect can provide a better time indication of performing beach nourishment in order to extend longevity. To find how storm variables are irrelevant, it is advised to investigate by testing whether it is a result of missing relevant variables or insufficient observations in the MLR model.

As noticed in this study, the number of observations is relatively low. Therefore, it is advised to compute the rest of the transect longevities of all the selected beach nourishments. In this way, more observations will be included in the dataset. Consequently, it will increase the probability of having useful information to analyse data and improve the model's accuracy.

As stated in this study, some of the regression coefficients determined by Gijsman et al. (2018) were not equivalent compared to the findings of this study. It is believed that the differences are mainly a result of different morpho- and hydrodynamic conditions and a smaller research area. To verify this, it is encouraged to apply this study method at a coastal area outside the Netherlands (e.g. coastline of Denmark) with a similar area size as the central Holland coast. These results can reveal whether the signs of the regression coefficients for the design aspects are universal or not. If the signs of the regression coefficients are equivalent, it is interesting to understand why different morpho- and hydrodynamic conditions do not affect the regression coefficients. On the other hand, if the signs of the regression coefficients are nonequivalent, it is interesting to understand how the different morpho- and hydrodynamic conditions affect the relationship between the design aspects and beach nourishment longevity.

Another recommendation is to apply this study to coastal areas such as the Delta (South of central Holland coast) and the Wadden (North of central Holland coast). These new studies can reveal whether the determined regression coefficients of design aspects (design volume per metre, design height and design length) are still valid for other coastal areas in the Netherlands. Furthermore, the findings can be insightful to understand the relationship between the design aspects and beach nourishment longevity along the entire Dutch coast.

8.3 Process-based Model

Process-based models (e.g. Delft3D and XBeach) can be helpful to understand how beach nourishment will evolve through time since it simulates the morpho- and hydrodynamic processes and impacts on the coast. By using these models, it can be verified whether the proposed design aspects in this study are equivalent to the model or not. It is recommended to simulate various design combinations of beach nourishments, to observe whether the simulations show the same behaviour as discussed in the study. If the results of the simulations do not show the same behaviour, it is advised to determine which factors have resulted in the difference. This acquired information can give a better insight into which data is missing during the analysis.

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A Appendix I

Appendix A represents all the computed longevities per transect (derived from MCL and beach volume) of all considered locations. In addition, for each beach nourishment and location the representative median longevity is presented. The colour in each cell displays the confidence level (high, moderate, or low) of the computed longevities.

Confidence level	🟩 High	🟨 Moderate	🟥 Low

Table A.1: Beach nourishment longevities of Julianadorp based on MCL in years.

Julianadorp	Year			
Transect	1992	1996	2003	2015
170	🟩 3.18	🟩 3.31	🟩 2.44	🟩 2.49
230	🟩 4.91	🟩 3.47	🟩 4.22	🟩 3.74
289	🟨 5.92	🟩 2.52	🟨 2.67	🟩 4.83
369	🟨 5.33	🟩 4.83	🟨 2.73	🟩 1.92
429	🟨 3.15		🟨 2.06	🟩 2.01
489	🟩 1.90		🟩 2.44	🟨 2.40
528	🟩 4.64		🟩 1.96	🟨 1.40

Med_n Beach	3.91	3.39	2.44	2.49
Med_n Location	2.94			

Table A.2: Beach nourishment longevities of Julianadorp based on beach volume in years.

Julianadorp	Year			
Transect	1992	1996	2004	2015
170	🟩 2.32	🟩 2.68	🟩 3.10	🟩 3.93
230	🟩 4.11	🟩 3.73	🟨 3.93	🟥 8.33
289	🟥 25.84	🟨 3.68	🟨 3.18	🟩 6.43
369	🟨 3.78	🟨 4.24	🟨 4.07	🟨 6.07
429	🟨 2.38		🟨 3.73	🟨 5.31
489	🟨 2.48		🟨 3.74	🟨 3.50
528	🟨 1.97		🟨 2.99	🟩 3.33

Med_n Beach	3.22	3.21	3.10	3.93
Med_n Location	3.21			

Table A.3: Beach nourishment longevities of Callantsoog based on MCL in years.

Callantsoog	Year		
Transect	1991	1996	2004
1137	🟩 4.87	🟨 2.53	🟨 13.78
1182	🟨 4.24	🟨 3.51	🟩 3.65
1228	🟨 3.40	🟨 2.50	🟨 11.35
1243	🟨 3.33	🟨 2.58	🟩 1.15
1258	🟨 5.51	🟨 2.90	🟨 5.15
1273	🟨 5.21	🟩 2.85	🟩 4.80
1288	🟩 6.53	🟩 3.17	🟩 1.56
1340	🟩 2.79	🟩 3.18	🟩 2.30

Med_n Beach	4.87	3.18	2.30
Med_n Location	3.18		

Table A.4: Beach nourishment longevities of Callantsoog based on beach volume in years.

Callantsoog	Year		
Transect	1991	1997	2004
1137	🟩 4.10	🟨 2.32	🟥 24.87
1182	🟨 5.03	🟨 3.76	🟨 5.86
1228	🟨 3.50	🟨 2.97	🟨 12.29
1243	🟩 3.49	🟨 3.13	🟨 4.08
1258	🟨 3.75	🟩 2.47	🟨 4.36
1273	🟨 3.19	🟩 2.94	🟨 6.88
1288	🟩 2.98	🟩 3.13	🟨 2.61
1340	🟨 3.00	🟨 2.97	🟨 2.50

Med_n Beach	3.49	2.94	
Med_n Location	3.21		

Table A.5: Beach nourishment longevities of Bergen aan Zee based on MCL in years.

Bergen aan Zee	Year		
Transect	1993	2005	2011
3175	0.88		2.71
3225	2.05	4.11	0.56
3250	2.62	3.63	1.43
3275	2.66	3.16	8.17

Med$_n$ Beach	2.62	4.11	1.63
Med$_n$ Location	2.62		

Table A.6: Beach nourishment longevities of Bergen aan Zee based on beach volume in years.

Bergen aan Zee	Year		
Transect	1993	2005	2011
3175	0.89		3.14
3225	1.19	3.82	0.96
3250	3.09	4.10	0.60
3275	6.58	3.64	0.81

Med$_n$ Beach	0.89	3.96	3.14
Med$_n$ Location	3.14		

Table A.7: Beach nourishment longevities of Egmond aan Zee based on MCL in years.

Egmond aan Zee	Year		
Transect	2000	2005	2011
3725	11.75	3.13	4.85
3750	4.30	3.80	8.05
3775	3.08	3.74	11.32
3800	3.54	8.90	5.20
3825	5.47	15.51	4.14
3850	7.90	15.02	2.01
3875	8.91	7.33	4.34

Med$_n$ Beach	3.31	3.77	5.03
Med$_n$ Location	3.77		

Table A.8: Beach nourishment longevities of Egmond aan Zee based on beach volume in years.

Egmond aan Zee	Year		
Transect	2000	2005	2011
3725	4.04	4.21	7.05
3750	4.37	8.89	2.74
3775	6.15	9.20	4.34
3800	9.06	36.35	4.73
3825	6.01	3.36	2.58
3850	5.01	3.82	0.28
3875	2.83	3.24	2.82

Med$_n$ Beach	3.93	3.73	7.05
Med$_n$ Location	3.93		

Table A.9: Beach nourishment longevities of Bloemendaal aan Zee based on MCL in years.

Bloemendaal aan Zee	Year	
Transect	1990	1993
6200	0.56	0.98
6225		1.50
6250	2.67	1.59
6275	2.43	4.99
6300	2.89	1.68
6325	3.44	1.63

Med$_n$ Beach		1.68
Med$_n$ Location	1.68	

Table A.10: Beach nourishment longevities of Bloemendaal aan Zee based on beach volume in years.

Bloemendaal aan Zee	Year	
Transect	1990	1993
6200	2.45	
6225	6.99	
6250	8.19	8.27
6275	3.52	
6300	1.81	
6325	1.55	3.34

Med$_n$ Beach	5.32	0
Med$_n$ Location	5.32	

Table A.11: Beach nourishment longevities of Scheveningen based on MCL in years.

Scheveningen	Year			
Transect	1975	1987	1991	1996
9925	4.43		0.83	6.85
9975	11.63	0.06	195.38	3.41
10025	2.52		3.78	2.85
10075	11.06	0.95	9.25	11.72

Med$_n$ Beach	11.06		0.83	3.13
Med$_n$ Location	3.13			

Table A.12: Beach nourishment longevities of Scheveningen based on beach volume in years.

Scheveningen	Year			
Transect	1975	1987	1991	1996
9925	4.75	2.68	3.60	4.54
9975	2.74	2.78	5.52	2.35
10025		5.26	3.80	2.27
10075		1.21	6.70	7.84

Med$_n$ Beach	4.75	3.24	3.70	2.35
Med$_n$ Location	3.47			

Table A.13: Beach nourishment longevities of Ter Heijde based on MCL in years.

Ter Heijde	Year		
Transect	1986	1993	1997
11034	2.86	2.33	10.67
11072	3.34	5.17	10.04
11109	1.74	3.75	5.19
11147	3.45	5.16	1.55
11176	2.66	4.61	4.79
11196	1.60	2.70	3.48
11221	3.97		3.07
11244	6.50		0.72

Med$_n$ Beach	2.76	3.75	4.13
Med$_n$ Location	3.75		

Table A.14: Beach nourishment longevities of Ter Heijde based on beach volume in years.

Ter Heijde	Year		
Transect	1986	1993	1997
11034	4.06	8.08	
11072	2.71	5.32	
11109	3.62		0.84
11147	8.35	6.65	0.67
11176	3.46	1.99	11.96
11196	3.17	6.21	1.43
11221	2.97		3.20
11244	3.21		0.75

Med$_n$ Beach	3.21		
Med$_n$ Location	3.21		