THE FORT OF THE FUTURE

REDEFINING RESILIENCE: DUTCH FORTS AS INSPIRATION FOR SELF-SUFFICIENT BUILDING DESIGN

Anne Eder
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft
a.eder@student.tudelft.nl

ABSTRACT

This paper explores the potential for self-sufficient, climate-resilient buildings in the Netherlands by examining historical forts of the Dutch Waterline and contemporary projects, through the lens of the interconnected self-sufficiency domains - water, energy and food. To facilitate comparison and draw actionable insights, the study introduces a Level of Self-Sufficiency (LoS) grading system. By combining lessons from the past and present, the study proposes a vision for the "fort of the future". The analysis highlights the relevance of historical design principles—such as self-sufficiency, resilience, passive techniques and landscape integration — in addressing contemporary challenges, like water overload, water scarcity and energy overload. Furthermore, emerging technological advancements make achieving higher levels of self-sufficiency increasingly feasible. However, due to regulatory constraints, technical challenges in water reuse and energy storage, and spatial limitations for food production, barriers for achieving full self-sufficiency remain. The paper concludes with a set of design principles and technical strategies to guide the creation of self-sufficient, climate-resilient buildings for future development.

KEYWORDS: ***Self-sufficiency, Climate-resilience, Building design, Water-Energy-Food, Level of Self-sufficiency, Dutch forts, Contemporary projects, Design principles, Design strategies***

1. INTRODUCTION

1.1 WATER AND ENERGY DEFICITS AND OVERLOADS IN THE NETHERLANDS

Globally, climate change has emerged as a major challenge in recent years, leading to more frequent events like extreme heat, heavy rainfall, floods and droughts, which pose risks to the built environment and public safety. Buildings significantly contribute to climate change, accounting for nearly 40% of global energy consumption and approximately one-third of greenhouse gas emissions, while also driving resource depletion (Okwandu, Akande and Nwokediegwu, 2024). Therefore, the way buildings are designed and constructed greatly affects the environment. Studies show that the building sector offers considerable potential for mitigating climate change and reducing carbon emissions (Andrić, Koc and Al-Ghamdi, 2019).

In response, both the building- and energy sector have already started shifting towards reducing greenhouse emissions by building more sustainably and implementing more renewable energy sources, such as solar and wind. However, due to dependency on natural circumstances, these energy sources come with the drawback that they deliver a fluctuating energy output (Sandhu and Thakur, 2014). During periods of high solar and wind energy production, combined with a low demand, the grid becomes overloaded, resulting in inefficiencies and wasted energy.

The Netherlands, with its temperate maritime climate, faces challenges due to rising temperatures and changing rainfall patterns, which lead to issues such as water overload during heavy downpours and water scarcity during drier summers (KNMI, 2023). Simultaneously, the Dutch energy grid, originally designed for a one-way flow of electricity, struggles with grid congestion caused by the rise of decentralized renewable energy sources (Netbeheer Nederland, 2019).

Architecture can play a vital role in addressing these stated challenges by meeting resource demands independently and thus off-grid. Self-sufficient buildings could help reduce issues like grid congestion and water deficits or overload. By managing their own demands and flows, these buildings reduce reliance on external systems, offering greater resilience and sustainability.

1.2 Definition of self-sufficiency

Self-sufficiency is a broad and subjective concept, often interpreted differently depending on individual perspectives. First of all, it is hard to define when a project can be seen as self-sufficient. For example, some may consider a building with solar panels on its roof to be self-sufficient because it generates its own energy. However, in situations where sunlight is unavailable, such as during the evening, the building cannot provide for their demand and therefore remains dependent on the grid for electricity. Secondly, it can be questioned whether a building is self-sufficient if it addresses only one domain, such as energy. To truly sustain a building's operations and meet the needs of its users, more internal flows must be considered. For instance, water and food systems play equally important roles in enabling a building to function independently from the grid.

It is essential to consider the interconnection between energy, water, and food systems, also referred to as "nexus", as actions in one domain frequently affect the others and have consequences for the ecosystems that sustain both natural resources and human activities (Javan *et al.*, 2024).

Therefore, *Self-sufficiency*, in this context, will refer to buildings or neighbourhoods capable of meeting their own needs for energy, water, and food. This implies a system that operates off-grid and ideally functions within a closed-loop system that minimizes waste and resource inputs. This approach involves integrating systems for renewable energy generation, energy storage, water collection and recycling, waste management, and food cultivation to enable the building to operate autonomously.

1.3 A Brief History of Self-Sufficiency In The Netherlands

Self-sufficient buildings are not a new concept in the Netherlands; in fact, they are rooted in the nation’s rich history with water. Water has been both a persistent enemy and a crucial ally to the Dutch. To protect and expand their land, they constructed dikes and drained marshes to create polders. However, with the creation of the Dutch Water Line, the Dutch ingeniously used water as a tool for protection. This 200-kilometer-long defence system used a network of dikes, locks, and canals to flood strategic areas, creating natural barriers against enemies (Hollandse Waterlinies, 2023). Across the country, five such defence lines were established between 1590-1972 (Steenbergen et al., 2009), as illustrated in Figure 1. These defence systems were hidden within open and green landscapes and were carefully designed to remain secret for a long time (Hamberg and Ros, no date). They were fortified with strongholds located on land that could not be flooded but held strategic importance for controlling the waterworks.

The forts were designed to operate autonomously, anticipating on the possibility of being completely surrounded by water. They incorporated integrated defence mechanisms and self-sustaining systems capable of temporarily supporting life within. By using stored and collected resources such as coal, wood, fossil fuels, food, and water, the forts could sustain themselves for limited periods. However, they still required occasional external supplies to continue operating in the long term. Meaning, they were designed to be “temporary-self-sufficient” or “resource-supported self-sufficient”, highlighting that while their system covered some of its own needs, they did not fully eliminate dependence on external resources.

Today, some forts continue to operate with a combination of historic and modern self-sustaining practices, which reflect a deep cultural connection to resilience and independence.

WATERLINES

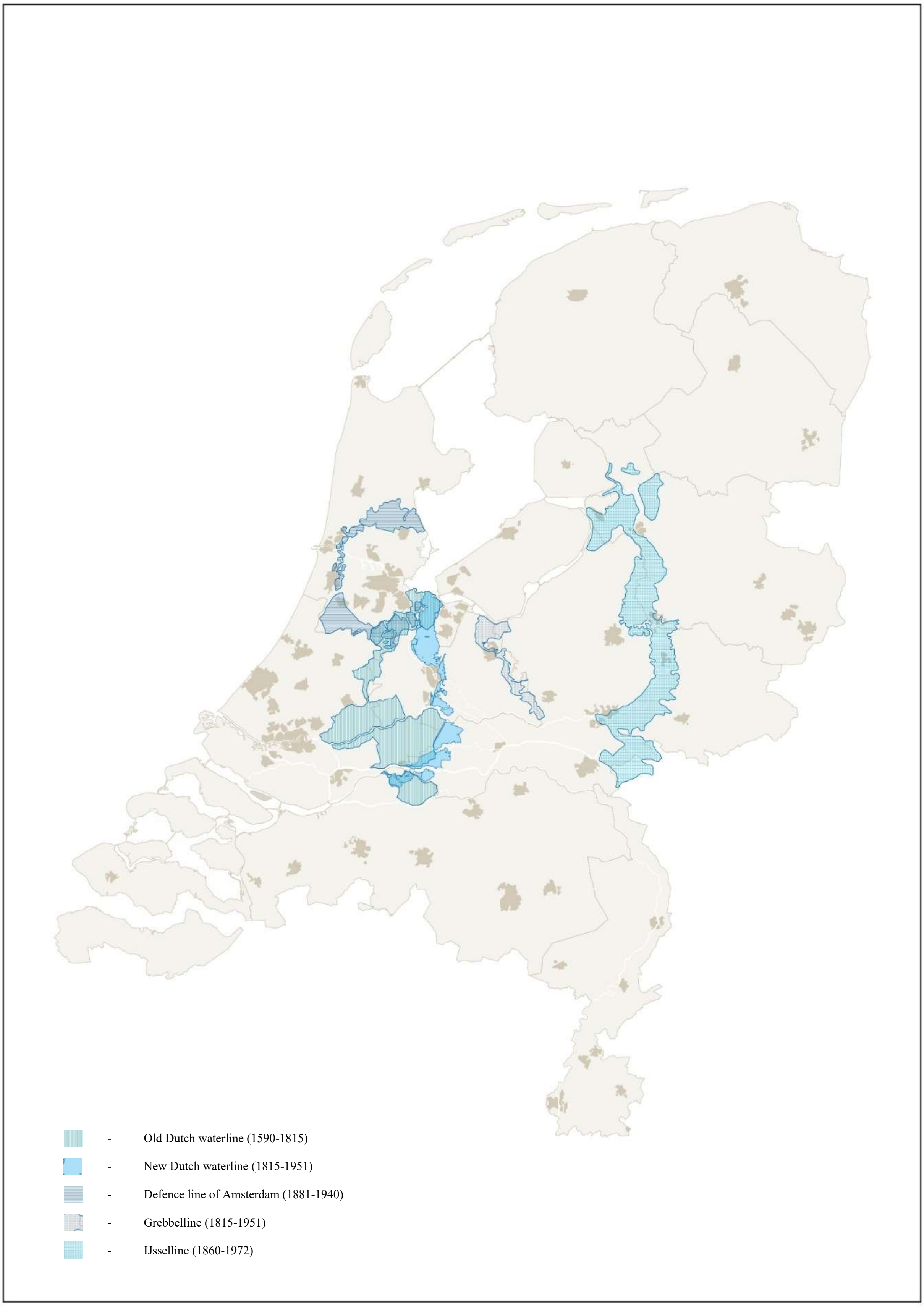


Figure 1. Water defence lines of the Netherlands (Steenbergen et al., 2009)

1.4 THESIS OBJECTIVE

As previously mentioned, the Netherlands faces pressing challenges related to both water overload and water scarcity, as well as an overloaded energy network. By studying the forts of the Dutch Water Line, we might be able to uncover valuable lessons from their self-sufficient systems and innovative designs. These historic structures were built to withstand periods of isolation, providing resources and resilience during sieges and enemy intrusions. The principles and strategies behind these forts may hold potential for translation into modern solutions that address today's challenges. Additionally, advancements in technology and contemporary sustainable projects offer opportunities to enhance these historic ideas with innovative approaches to resource management and climate-resilient design.

The objective of this thesis is to identify key design principles and strategies for "the fort of the future"—a climate-resilient, self-sufficient building capable of addressing the pressing challenges of todays and tomorrow's world. This leads to the following thematic research question:

What design principles and strategies can be derived from the Dutch Water line forts and contemporary projects in the Netherlands to create a self-sufficient, climate-resilient building for the future?

This research will explore both the historical and modern dimensions of self-sufficient design by examining the functioning of the forts of the Dutch Water Line alongside innovative contemporary projects in the Netherlands. The goal is to develop a framework for the design of climate-resilient, self-sufficient buildings that can meet their demands for water, energy, and potentially food.

It is important to acknowledge, however, that defining self-sufficiency can be complex, as the concept often varies depending on context, feasibility and interpretation (Chapter 1.2). To address this, —water, energy, and food—will serve as the three key domains for evaluation. These domains will provide a structured basis for comparing and assessing the degree of self-sufficiency in various projects. Furthermore, they will form the analytical lens through which the concept of self-sufficiency will be studied in these projects.

The following sub questions will help structure and build up de research to be able to answer the main thematic research question in the end:

1. **Self-sufficient, climate resilient buildings**
   Which characteristics and design strategies make a building self-sufficient and climate resilient?

2. **The Dutch Waterline and their Forts**
   What can be learned from the historical forts of the Dutch Waterline regarding achieving self-sufficiency?

3. **Contemporary projects**
   What innovative strategies and systems in contemporary buildings or neighbourhoods in the Netherlands can enhance self-sufficiency in water, energy, and food?

2. METHODOLOGY

2.1 Research Setup

As the goal of this thesis is to define design principles and strategies for the "Fort of the Future"—a climate-resilient, self-sufficient building designed to address the pressing challenges of today and the future, it is crucial to first clarify what constitutes a self-sufficient, climate-resilient building. This foundational understanding will be developed through secondary data collection via an extensive literature review.

The next step involves exploring how such a building can be realized and assess the potential for buildings in the Netherlands to achieve true self-sufficiency. To do so, an analysis of both historical and contemporary projects will be conducted. To examine these projects, a framework will be developed to systematically evaluate and compare their **Level of Self-Sufficiency (LoS)**.

A qualitative analysis of forts from the Dutch Waterline, alongside contemporary building projects, will be executed to understand the technologies and architectural systems employed to achieve grid independence. By grading these projects on their LoS, the analysis aims to identify which approaches are most effective and which are less successful. This grading system will ensure consistent comparisons, determining the strengths and limitations of historic and current self-sufficient designs. The insights gained from this analysis will provide valuable guidance for designing the Fort of the Future and advancing self-sufficient building design in the Netherlands.

The following sections elaborate on the setup of the LoS grading system and provide an overview of the selected building projects, including both forts and contemporary examples, to be analysed in this study. Figure 2 shows the visualisation of the research setup.

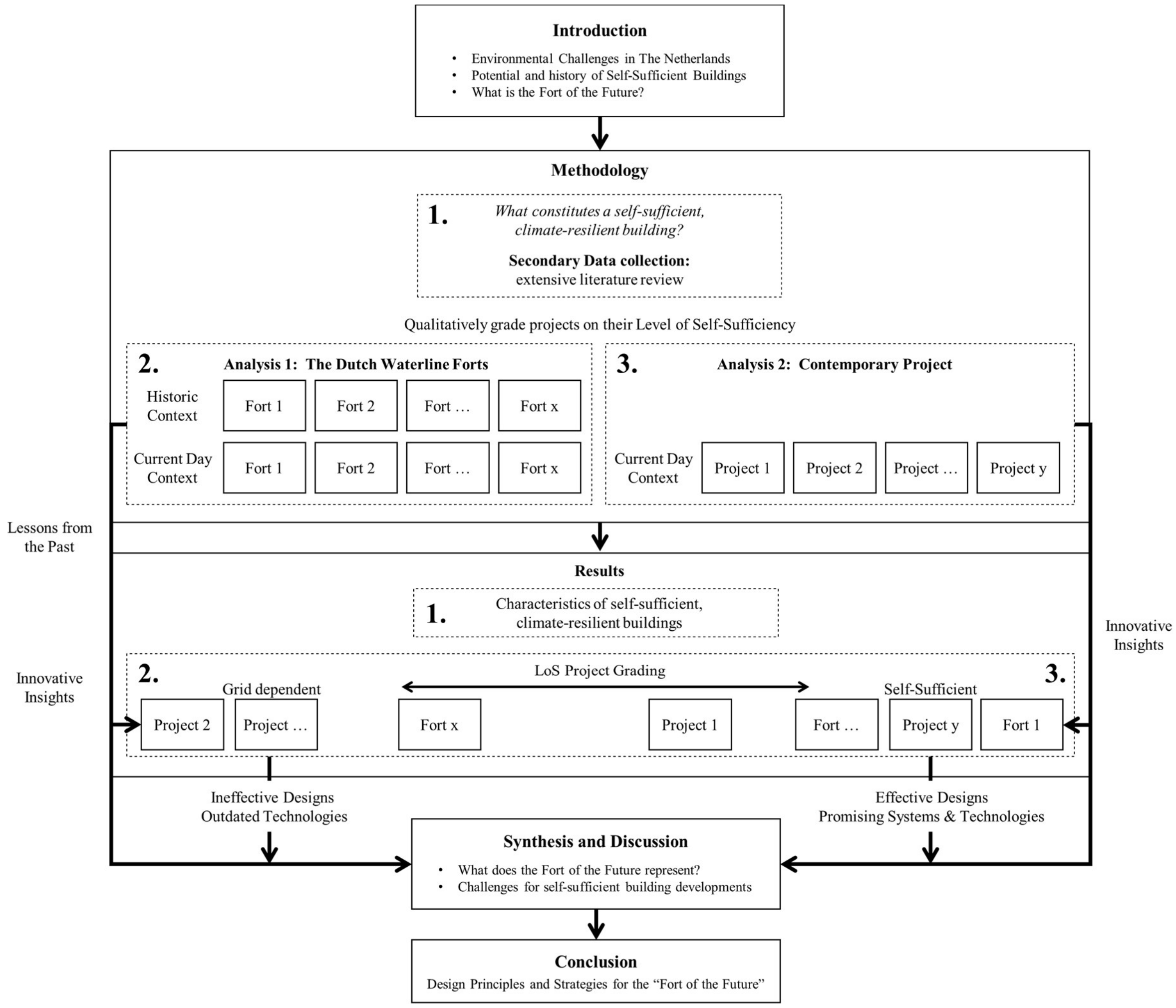


Figure 2. Research setup scheme

2.2 LoS Grading system

In this thesis, a building is considered truly self-sufficient if it operates independently from external grids within a closed-loop system where energy, water, and food resources are effectively managed, reused, and recycled. To evaluate a building's Level of Self-Sufficiency (LoS), key aspects within these three interconnected domains have been identified based on insights from literature and analysis. The key components are as follows:

- **Water Domain:** Focuses on water supply, water buffering, and water reuse and treatment.
- **Energy Domain:** Includes of energy supply, energy storage, insulation, heating, cooling, ventilation, and the use of passive design techniques.
- **Food Domain:** Addresses food supply and waste management.

These aspects were chosen because they represent the fundamental components of a self-sufficient system. Without addressing water supply and treatment, energy production and storage, or food supply and waste, achieving independence from external resources is not possible. Furthermore, as discussed in Chapter 1.2, the three domains are interconnected, meaning actions taken in one domain often affect the others. For instance, cultivating food requires additional water and increases energy demand when supported by irrigation systems. On the other hand, rainwater reuse can reduce the need for potable water typically used for food production and Organic waste can be transformed into fertilizers or biogas, which can subsequently be used to support food cultivation or generate energy. Understanding these interdependencies is crucial, as systems within each domain can either support one another or create conflicts.

This grading system, outlined in the following tables, is designed to assess if a project addresses the three domains and their associated aspects, providing a framework for evaluating self-sufficiency in buildings. For example, on the water supply theme, a project relying on water from the municipal infrastructure, would score 1 on the qualitative LoS scale, indicating full dependency on the grid. In contrast, a project with its own drinking water supply, storage and wastewater treatment would score 4, demonstrating full self-sufficiency.

Grid dependent ⟷ Self-sufficient

	1	2	3	4
Water supply	External	Internal (for plants, toilets)	Mostly internal (drinking water external)	Fully internal (also drinking water)
Water buffer/ storage	No buffer	Small buffer (green roofs)	Medium size buffer (for a temporary supply of water)	Big buffer to provide for all year round need of water
Water reuse/ treatment	No internal water reuse or treatment	Water reuse external treatment	Water reuse and treatment	Water reuse and treatment (in closed loop)

Table 1. Key aspects within the water domain

Grid dependent ⟷ Self-sufficient

	1	2	3	4
Food supply	External supply	Temporary Storage	Little own production	Fully self-providing
Food waste	No processing			Processing in closed loop

Table 2. Key aspects within the food domain

Grid dependent ⟵⟶ Self-sufficient

	1	2	3	4
Energy supply	External	Temporary energy supply by fossil fuels	Little own production	Fully self-providing (with green energy)
Energy storage	No	Yes, can temporarily cover daily needs	Yes, can temporarily cover seasonal needs	Yes, can cover all year round needs
Insulation	Bad insulated			Well insulated
Heating	No	Yes, but with fossil fuels or conventional systems	Yes, with heatpumps and LTH	Yes, with passive techniques)
Cooling	No	Yes, with conventional cooling	Yes, with heatpumps	Yes, with passive techniques
Ventilation	No	Yes	Yes, with heat recovery	Yes, with passive techniques
Passive techniques	No	Minor use	Medium use	Advanced use

Table 3. Key aspects within the energy domain

2.3 Project Analysis

To identify and compare building systems, technologies, and concepts, *historic forts*, *current-day forts*, and *contemporary project*s will be analysed and graded by the using the LoS grading system described above. The findings will inform the design principles for the "Fort of the Future," ensuring it achieves a high level of self-sufficiency across the domains water, energy and food. The following projects have been selected, and their locations across the Netherlands are illustrated in Figure 3:

Analysis 1: The Forts of the Dutch Waterline

These forts were examined in terms of both their historical and present-day operations and evaluated using the LoS grading outlined in the Methodology.

1. Historic Forts

The Historic forts will serve as reference projects for understanding the building systems historically implemented to achieve self-sufficiency and evaluating their effectiveness. The forts to be analysed are **Lighthouse Island** and **Fort Island Pampus** in the province of North-Holland, **Fort Honswijk** in the province of Utrecht and **Fort Everdingen** and **Fort Pannerden** in the province of Gelderland. These forts were chosen because they have been adapted for contemporary uses and incorporated innovative new technologies during their transformation. Additionally, the selection includes different types of forts with varied layouts and locations, potentially revealing differences and similarities in the integration and placement of these systems based on their geographical and structural contexts.

2. Current-Day Forts

This analysis focuses on investigating the systems currently implemented in the forts. The objective is to analyse the present-day adaptations of the forts and evaluate whether they achieve a higher level of self-sufficiency compared to their historic function.

Analysis 2: Contemporary Projects

Analysing recent technological advancements and innovative approaches in contemporary projects. The objective is to identify additional building systems and technologies that could inform the design of the "Fort of the Future." The contemporary projects selected for this analysis were chosen based on their innovative approaches to achieving self-sufficiency in the domains water, energy, and/or food. The analysed projects are **Four element hotel** and **Schoonschip** located in Amsterdam, **Proyecto roble** located in Tilburg, **Floating farm** located in Rotterdam and **ReGen village** in Almere.

It is important to recognize that generalizing the project analysis is difficult due to the temporal differences. The forts were well-designed for their time and could be considered "self-sufficient" based on the standards and technologies available then. However, these standards and technologies differ significantly from those we have today. As a result, the analysis of the historical functioning of the forts were approached from a historical perspective, considering the limitations and resources available during that period. In contrast, the modern adaptations of the forts and contemporary projects were evaluated considering current regulations and technological possibilities.

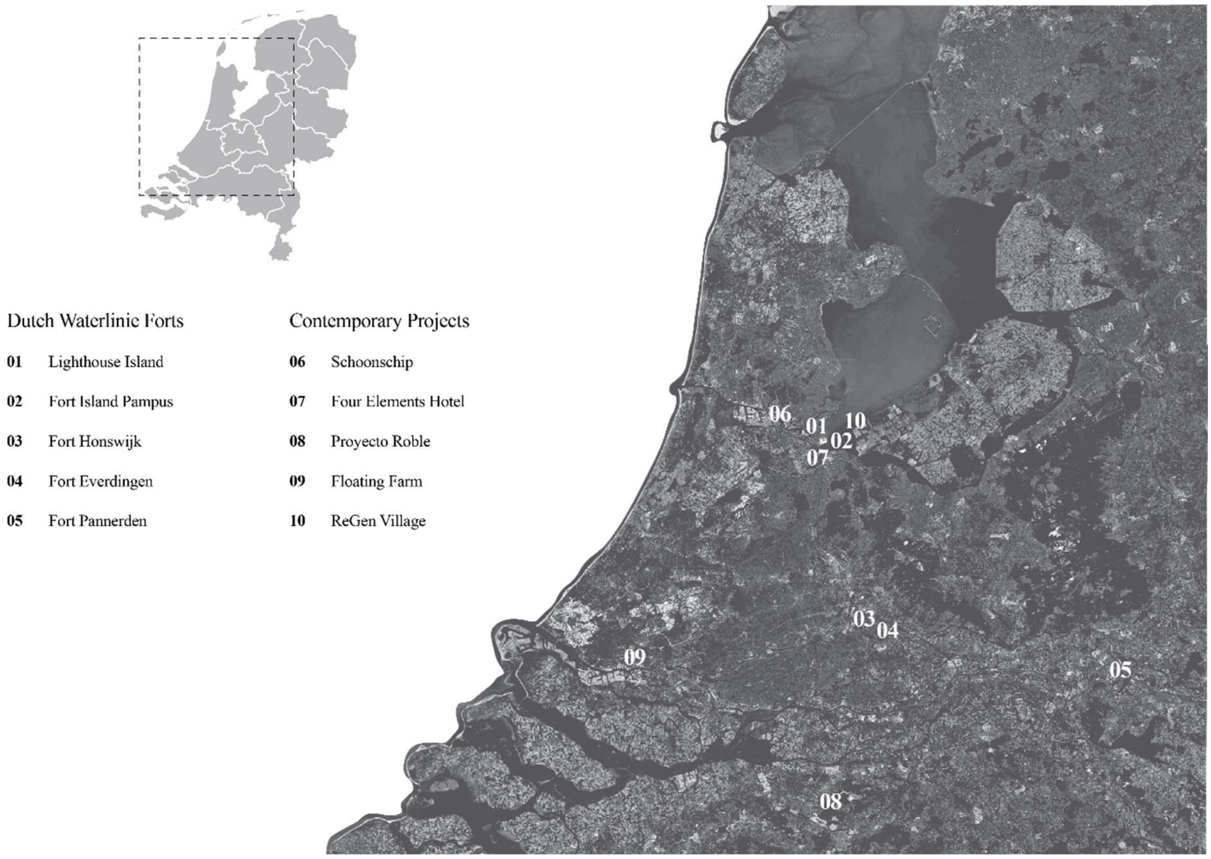


Figure 3. Map project locations

3. RESULTS

3.1 Why Self-sufficient, Climate Resilient Buildings

As this research seeks to define the design principles and strategies for a self-sufficient, climate-resilient building in the Netherlands, it is essential to understand the potential such a concept holds for mitigating environmental impact and adapting to climate change. Self-sufficient, climate-resilient buildings are designed to operate independently from external resources, such as centralized energy grids and water supplies, while being equipped to withstand the challenges posed by a changing climate. By integrating advanced systems and innovative technologies, these buildings aim to minimize their environmental footprint, adapt to climate risks, and meet their own energy, water, and resource needs.

One of the defining characteristics of self-sufficient buildings is **Water self-sufficiency.** Systems like rainwater harvesting, greywater recycling, and on-site wastewater treatment enable efficient reuse, reducing reliance on natural freshwater sources. Efficient water fixtures further minimize consumption, while applications like green roofs and rainwater storage possibilities alleviate pressure on municipal systems and enhance resilience to droughts and floods (Marquez, 2023). By integrating water self-sufficiency into their design, these buildings address one of the most pressing resource challenges posed by climate change.

Energy independence is equally crucial in these buildings. By using renewable energy sources such as solar panels, wind turbines, or geothermal systems, these buildings reduce their reliance on fossil fuels, enabling them to meet their energy needs more sustainably. This approach not only significantly lowers their carbon footprint but also helps to mitigate greenhouse gas emissions. However, these renewable energy systems, along with energy storage technologies (such as batteries), required to provide reliable power during periods of low production, rely heavily on critical materials This dependency contributes to resource depletion. To address this issue, it is essential to minimize the use of such materials and high-tech systems wherever possible.

This can be achieved through energy-efficient design, which incorporates **passive design strategies**, like passive heating, cooling, and optimized natural lighting (Marquez, 2023). Additionally, **nature-based solutions**, such as green roofs, rainwater harvesting systems, and tree planting (UNEP and SEfficiency, 2021), can further reduce overall energy consumption and demand. These strategies not only mitigate climate risks but also deliver co-benefits like improved air quality, enhanced biodiversity, better water management, and stabilized temperatures (McDade *et al.*, 2020). Complementing this, blue infrastructure, such as ponds and wetlands, provides cooling effects, reduces urban heat islands, prevents flooding, and improves water retention (UNEP and SEfficiency, 2021).

In some cases, self-sufficient buildings integrate **food production** systems, such as rooftop gardens, vertical farming, or hydroponic systems. These features support localised food production, enhance biodiversity, and improve environmental performance by absorbing carbon dioxide and improving air quality.

Self-sufficient buildings are also designed with **adaptability** in mind to withstand extreme weather events and other climate-related risks. Enhanced insulation, flood-resistant foundations, and advanced cooling systems ensure these structures remain functional and efficient in varying conditions. The use of durable, low-carbon materials, in combination with features like passive cooling, natural ventilation, and (natural) shading systems customised to specific climates, enhance indoor comfort while reducing energy demand (Marquez, 2023 & UNEP and SEfficiency, 2021).

CLIMATE-BASED DESIGN

For instance, in cold and temperate climates, passive design techniques maximize heat gain and retention through strategies like south-facing orientations, thermal mass for heat storage, Trombe or water walls, and solar chimneys for natural ventilation (UNEP and SEfficiency, 2021). In hotter climates or during hot summer days in temperate climates, proper alignment with prevailing winds, strategic vegetation placement, (adjustable) shading systems, green roofs, and passive cooling systems mitigate heat gain while reducing energy demand (UNEP and SEfficiency, 2021). Reusing traditional elements, such as wind towers or courtyards which facilitate shading, can also address climate-specific challenges effectively.

Ultimately, self-sufficient, climate-resilient buildings are not only a response to the urgent need for sustainability but also help tackle challenges posed by climate change. By closing resource loops, integrating renewable systems, mitigating demands and fostering adaptability, these buildings set a benchmark for environmentally responsible and future-proof architecture.

3.2 The Dutch Waterline and their forts

To assess what can be learned from the historical forts of the Dutch Waterline in terms of their self-sufficient building systems and the way they were designed, five forts with contemporary functions were selected for this study: Vuurtoreneiland, Forteiland Pampus, Fort Honswijk, Fort Everdingen, and Fort Pannerden. These forts were examined in terms of both their historical and present-day operations and evaluated using the LoS grading outlined in the Methodology.

The complete dataset and the compiled catalogue are included in the booklet. The following paragraphs present the results from this analysis.

Historical Operations

Typology and layout

The forts analysed reveal a closed typology, reflecting their military function, with typically only one entrance for easy defence. According to Hamberg and Ros (no date), the design and function of each fort were shaped by the terrain. For example, small, simple forts guarded narrow roads, while larger, more complex ones protected higher ground with multiple access points.

Although the form and layout of the forts may be different, they all featured kitchens, food storage, toilets, black water pits and supplies of fuel like coal and petroleum. Most importantly was that drinking water was self-supplied by rain collection and wells, while food and resources for energy production were sourced from warehouses and factories in the hinterland, ensuring the forts could function independently during conflict (Hamberg and Ros, no date).

Forts as a Landscape

The forts were designed to blend seamlessly into the landscape, using low structures and carefully placed vegetation to camouflage them and their weaponry (Harlaar, Kwant, and Stichting Liniebreed Ondernemen, 2015). Over time, especially after losing their military function, these forts have transformed into vibrant hotspots for biodiversity. Their unique construction and location, featuring imported sand, fertile soil, varying elevations, and isolated moats filled with high-quality water, have created ideal habitats for a wide range of species, including birds, bats, butterflies, mice, fish, and reptiles (Harlaar, Kwant, and Stichting Liniebreed Ondernemen, 2015).

Despite being built with non-biobased materials like concrete, the forts demonstrate how buildings can function in harmony with nature. Their strength and effectiveness as defensive structures were inherently tied to their integration with the natural environment, while the thriving biodiversity they now support further demonstrates how architecture and nature can work together.

Functioning of Forts and their self-sufficient systems

Forts were designed as self-sufficient structures deeply integrated with their surrounding landscape, making them become a part of it. Their architecture leveraged natural features for defence and self-provision. It used the landscape to stay hidden from its enemies but also used nature and its natural materials for better water management, drinking water production and the harvesting of firewood.

Drinking water was vital, that's why rainwater was captured and purified using the roof-ground layers or a sand-gravel filter. Food and energy sources, as oil, coal and wood, were stored to ensure temporary independence during sieges. Thick, earth-embedded walls maintained a stable indoor climate, natural ventilation provided enough fresh air and wood stoves were used to supply the additional need for heating. These features allowed forts to function as isolated, temporary self-providing systems capable of enduring long-term periods without external support.

The analysis reveals that the forts were only truly self-sufficient in the domain of water and even that came with limitations. The troops were heavily reliant on rainfall and the time required for precipitation to be purified and directed to the clean water basin. Therefore, during longer periods without rain, their water self-sufficiency was also temporary unless the fort had access to a groundwater well as a secondary water source, such as Fort Honswijk and Fort Everdingen.

Still, capturing and purifying rainwater by using a green roof or additional filtering system offers a simple and effective way to ensure an additional water supply. Furthermore, making use of thermal mass by thick, earth-embedded walls can provide a relatively stable indoor climate and effectively store thermal energy, such as generated heat. The integration of natural ventilation systems was thoughtfully designed and highly effective, particularly when combined with wood stoves. The stoves enhanced natural airflow by amplifying the draught, significantly improving ventilation efficiency. This was crucial for the survival of the troops, as proper ventilation was essential to mitigate the flue gases produced by the artillery used during defence.

PRESENT-DAY OPERATIONS

Functioning of Forts and their self-sufficient systems

The adapted forts now benefit from advancements in technology, particularly in the domains of energy and water management. For energy production, most forts rely on solar panels and/or wind turbines, with one project also using hydropower from the adjacent river. However, not all forts have integrated energy storage systems, which limits their ability to achieve full energy self-sufficiency due to the fluctuating output of renewable sources like wind and sun. Without sufficient storage, additional energy from the grid is still needed during periods of low production.

For water, many forts retain their historic rainwater harvesting systems, but these systems no longer meet the standards for drinking water without additional treatment. The same applies to the groundwater wells. As a result, these systems are now primarily repurposed for non-potable uses, such as irrigation or toilet flushing. One fort, however, has taken a more innovative approach: Fort Everdingen renovated its rainwater harvesting system to brew beer and provide heating and cooling, while still relying on external water grids for drinking water, as do Fort Honswijk and Fort Pannerden. In contrast, Forteiland Pampus and Vuurtoreneiland have adopted advanced technologies to produce drinking water themselves. Their systems filter water from the IJmeer and Markermeer using sand-gravel filters, nanofiltration, and UV disinfection, producing up to 20,000 liters per day (Klip, 2023). Vuurtoreneiland also stands out for its wastewater treatment, using a helophyte filter system to clean water before discharging it into surface water. The other forts, by comparison, still rely on historic sewage pits or are connected to modern sewage systems.

Food production remains the most challenging aspect of self-sufficiency. Three of the five forts have established vegetable gardens for small-scale local production, but these gardens are insufficient to meet their full food demands. Consequently, food production still depends on external supplies. However, innovations like Pampus' biodigester, which processes organic waste into biogas for energy and compost for the vegetable garden, showcase creative approaches to reducing waste and enhancing sustainability.

LEVEL OF SELF-SUFFICIENCY GRADING: PAST VS PRESENT

The grading overview of the forts (Table 4) shows that, in the past all forts scored high in the domain of water, with Fort Honswijk, Fort Everdingen, and Fort Pannerden achieving even higher scores due to the use of additional ground wells. The forts relied on similar techniques and systems, with energy and food provision being storage-based, allowing them to operate independently for short periods.

In their current function, the three most water-efficient forts have seen their scores drop from 4 to 2. This is because ground wells can no longer be used without expensive water purification systems to meet today’s drinking water standards. Since these forts are connected to the mainland, it was more practical to integrate with the water grid, reducing their self-sufficiency.

In contrast, Vuurtoreneiland and Forteiland Pampus have improved their water self-sufficiency, as their island locations made grid connections impractical. Both now operate independent drinking water purification systems that process water from the IJmeer, with Vuurtoreneiland also employing a helophyte filter for wastewater treatment. In terms of energy, both forts use solar panels, solar collectors or PVT panels, heat pumps, and energy or thermal storage systems. In food production, Forteiland Pampus stands out with its vegetable garden and a biodigester that converts organic waste into compost and biogas, creating a relatively closed system, demonstrating major progress towards self-sufficiency.

Past

	Vuurtoreneiland	Forteiland Pampus	Fort Honswijk	Fort Everdingen	Fort Pannerden
Water	●●●○	●●●○	●●●●	●●●●	●●●●
Energy	●●○○	●●○○	●●○○	●●○○	●●○○
Food	●●○○	●●○○	●●○○	●●○○	●●○○

Present

	Vuurtoreneiland	Forteiland Pampus	Fort Honswijk	Fort Everdingen	Fort Pannerden
Water	●●●●	●●●●	●●○○	●●●○	●●○○
Energy	●●●○	●●●○	●●○○	●●○○	●●○○
Food	●○○○	●●●●	●●○○	●●○○	●○○○

Table 4. LoS grading of the historical forts and their present functionality

CONCLUSION

When comparing past and present Levels of Self-sufficiency, it is evident that not all forts are more self-sufficient today. This variation is influenced by the differing ambitions of project developers. Some, like Forteiland Pampus and Vuurtoreneiland, have advanced the concept by blending historic practices with modern technologies to create localized systems that meet environmental goals. However, other forts have shifted away from self-sufficiency, relying instead on connections to mainland water, energy, and wastewater infrastructure, transitioning their role from a localised to a more delocalised functionality.

The analysis reveals that while nearly self-sufficient energy and water systems are achievable with advanced technologies, full self-sufficiency remains a challenge. Efficient energy storage solutions are crucial for consistent power availability, while water systems require effective wastewater treatment and reuse. Limited space hinders full food self-sufficiency, though small-scale production and partial food waste management are viable and beneficial. Ultimately, closing the loop across energy, water, and food systems is essential to achieving full self-sufficiency, but it requires innovative solutions and careful balancing of resources.

3.3 Contemporary Projects

Contemporary buildings in the Netherlands were analysed for their innovative use of the natural environment to achieve self-sufficiency in water, energy, and food, or to reduce their environmental impact and resource needs. The projects examined include Schoonschip, Four Elements Hotel, Proyecto Roble, Floating Farm, and ReGen Village. The findings, summarized by the three domains and key innovations, are as follows:

Schoonschip

This floating neighbourhood integrates water as a central design element, emphasizing resilience to sea-level rise and collaboration with the aquatic environment.

WATER	Green roofs buffer heavy rainfall, some homes harvest rainwater for partial supply, and water-efficient showers and vacuum toilets reduce the demand for water. Blackwater is treated via an innovative digester that produces biogas and fertilizer. However, centralized systems are still used for greywater treatment and drinking water supply.
ENERGY	Homes are well-insulated and use passive solar heat, PV panels, solar collectors, and aqua thermal heatpumps for energy and heating. Energy is stored in lithium-ion batteries and shared via a smart grid. Additional energy, if needed, is bought from a sustainable provider.
FOOD	While food production is absent, residents are encouraged to purchase seasonal, local food and make collective purchases from nearby farms to reduce impact.

Project-information gathered from:
(Schoonschip, no date & Greenprint Schoonschip, no date)

Four Elements Hotel

The hotel showcases innovative energy solutions through natural ventilation and climate-responsive design but underutilizes water and food domains.

WATER	No rainwater harvesting or water reuse is implemented.
ENERGY	The building uses the Earth, wind and Fire concept, which consists of passive systems like a climate cascade, solar chimney, and Ventec roof for ventilation and temperature regulation. This is supported by a thermal energy storage underground in combination with heat pumps. Surplus energy is fed back to the grid. Shower water heat recovery further enhances efficiency.
FOOD	No food production or waste treatment is present, limiting its self-sufficiency potential.

Project-information gathered from:
(OZ Architect, 2019; Smith, 2019 & De Ingenieur, 2019)

Proyecto Roble

This office building emphasizes innovative solutions in water and energy.

WATER	The roof consists of a helophyte green roof which is used to collected rainwater and treats it so that it can be used for toilet reuse. Greywater produced in the building is as well purified by the helophyte green roof, which doubles as functional greenery, and treated wastewater is safely discharged or reused for toilets.
ENERGY	PV panels and an air heat pump provide energy and heating, supplemented by a loam stove fuelled with left over branches from trimming. A nearby pond reflects sunlight into the building, enhancing natural lighting and heating in winter, which is a very smart way to reduce the need for artificial lightning and therefore energy use.
FOOD	Food production is not integrated into the design.

Project-information gathered from:
(Équipe, no date & Van Helvoirt Groenprojecten, no date)

Floating Farm

This project excels in food production while also addressing water and energy needs.

WATER	Rainwater is collected, filtered, and used for livestock and food cultivation. Cow manure and urine are processed to yield clean water, which is discharged into surface water.
ENERGY	Floating solar panels generate electricity, with surplus fed back to the grid.
FOOD	Cows are fed local food waste (e.g., potato scraps and brewers' grains). From the cow’s milk is produced and their manure is processed into fertilizer. Fruits and vegetables are grown in the basement using aquaponics, supported by the collected rainwater.

Project-information gathered from:
(Frearson, 2019, Goldsmith, 2023 & Dogan, 2024)

ReGen Village

This ambitious project envisions a self-sufficient neighbourhood that integrates water, energy, and food systems in a nearly closed loop.

WATER	Rainwater is harvested, filtered, and reused for vertical farming. Grey and black water are treated via helophyte filtration and reused for gardens or safely discharged.
ENERGY	PV panels and biogas systems generate electricity, which is distributed through a smart grid, with surplus used for electric car charging stations. Low-temperature heating is achieved with an air heat pump, and greenhouses preheat incoming air in winter.
FOOD	Vertical farming, aquaponics and seasonal gardens provide fruits and vegetables, while livestock, and fish contribute protein. Non-compostable bio-waste produces biogas, and compost feeds again the livestock through soldier flies.

Project-information gathered from:
(Effekt, 2016, Boddchaert, 2022)

LEVEL OF SELF-SUFFICIENCY GRADING

As shown in Table 5, three projects perform well in the water domain. However, none achieves full self-sufficiency, as they still rely on the water grid for drinking water supply. In the energy domain, one project achieves the highest score and three achieve 3 out of 4, demonstrating that energy self-sufficiency is feasible, but remains a significant challenge due to energy storage difficulties. In the food domain, two projects, the ReGen Village and the Floating Fram, score 4 out of 4. The Floating Farms functionality, however, differs from other projects, as it does not house humans. While it produces dairy products and fruits and vegetables for human consumption, the project primarily focuses on providing food and water for livestock and processing their waste, which can be done using a relatively small area. Therefore, its high score is due to the lower demands of the animals compared to humans, which makes a nearly closed-loop design possible. The ReGen village on the other hand, scores high because it incorporates sufficient space for agricultural operations to support full food self-sufficiency.

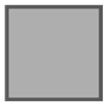
	Schoonschip	Four elements hotel	Proyecto Roble	Floating farm	ReGen village
Water	●●○○	●○○○	●●●○	●●●●	●●●●
Energy	●●●○	●●●●	●●●○	●●○○	●●●○
Food	●○○○	●○○○	●○○○	●●●●	●●●●
Project Scale					

Table 5. LoS grading of the contemporary projects

CONCLUSION

The analysed contemporary projects demonstrate innovative approaches to self-sufficiency in water, energy, and food. While some focus on specific domains (e.g., Floating Farm excels in food production, Four Elements Hotel in energy), others, like ReGen Village, aim for a more integrated approach. Together, these examples highlight the potential of combining passive techniques, local resources, and advanced systems to create sustainable and resilient buildings.

4. SYNTHESIS AND DISCUSSION

4.1 SYNTHESIS

The analysis reveals that the modern adaptation of Fort Island Pampus (4/3/4) and the ReGen Village (3/4/4) achieve the highest scores on the Level of Self-Sufficiency (LoS) scale. This is largely due to the developers' clear ambition to create off-grid systems, incorporating all three aspects—energy, water, and food—to the greatest extent possible. Despite these efforts, both projects still face challenges in fully addressing certain aspects of self-sufficiency. Nevertheless, they serve as valuable reference projects for envisioning what a self-sufficient fort of today might look like, while also offering inspiration and innovative ideas for the design of the fort of the future.

LESSONS FROM HISTORICAL FORTS AND THE VISION FOR THE FUTURE

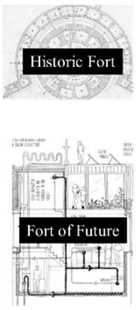
When interpreting the findings from the historical forts and their modern functions, the analysis revealed that the historical forts represented resilient structures designed to withstand bombs and attacks, offering safety to their occupants and making surviving possible. They provided temporary self-sufficiency, relied on passive techniques and local resources, and were seamlessly integrated into the landscape to remain hidden from enemies and for practical benefits, such as purifying water. The forts' effectiveness depended on military cooperation, with each occupant playing a vital role in the fort's operation.

When translating these historical design principles to address present and future challenges, including sustainability considerations, it becomes clear that these design principles remain remarkably relevant.

What does the Fort of the Future represent?

The fort of the future is a resilient structure, harmoniously integrated with its surroundings, designed to withstand external climate influences while fostering self-sufficiency. It operates as an independent system, working in synergy with nature and the landscape. By employing passive techniques for heating, cooling, lighting and ventilation, it minimizes energy demands, and together with active techniques it maximizes efficiency. Beyond its functional aspects, the modern fort also fosters communal living and recreation, providing a safe haven that supports residents' health and well-being. Its residents live collaboratively, sharing spaces and responsibilities, cultivating a sense of connection and mutual care.

The fort of the future reimagines historical principles through a contemporary lens, to create a sustainable, self-sufficient, and socially enriching environment for its inhabitants.



Temporary Self-Providing	Bomb Resilience	Integration in Landscape	Passive Techniques	User Collaboration	Safety	Surviving
↓	↓	↓	↓	↓	↓	↓
Self-Providing	Climate Resilience	Integration with the Environment	Passive & Active Techniques	Communal living	Recreation	Health & well-being

Figure 4. Design principles of the forts of the past and the fort of the future

4.2 Discussion

Several challenges emerged during the research, highlighting potential obstacles to developing a self-sufficient building in the Netherlands across the domains of water, energy, and food self-sufficiency.

Self-sufficiency in the Domain Water

Achieving full water self-sufficiency remains difficult due to regulatory and technical barriers. For example, while using rainwater for drinking is conceptually appealing, studies show it meets only 26% of daily demand due to losses and the need to divert the first flush (Bertelkamp et al., 2018). High purification costs and energy demands make it more expensive than tap water, even in neighbourhood-scale systems (Jorritsma, 2024). However, rainwater remains valuable for non-potable uses, such as irrigation, and in mitigating drought impacts. Drinking water regulations further complicate decentralization efforts. Since a drinking water contamination incident in Utrecht in 2001, it became illegal to use household water for purposes other than toilet flushing, with only licensed companies allowed to supply drinking water (Bertelkamp et al., 2018). Similarly, wastewater management policies require buildings in urban areas to connect to the sewage system, while rural areas must use individual treatment systems. An experimental approach in Almere Oosterwold, which employed helophyte filters for wastewater treatment, encountered significant issues, ultimately resulting in reconnections to centralized systems (Lokale wet- en regelgeving, 2022). These examples illustrate the substantial barriers to achieving water self-sufficiency under current practices and policies.

Self-sufficiency in the Domain Energy

Achieving energy self-sufficiency through renewable sources like solar and wind energy requires effective energy storage solutions to manage fluctuating power outputs. While current battery technologies can easily bridge short-term gaps, such as overnight energy needs, addressing seasonal storage remains a significant challenge. Technologies such as hydrogen storage, where excess energy is converted to hydrogen and later reconverted to electricity, are a potential solution but come with significant energy loss during the conversion process. Emerging technologies like saltwater batteries show promise as sustainable and efficient storage options; however, they are still in the developmental stage and not yet commercially viable. Long-term advancements in energy storage technology will be critical to making self-sufficient energy systems more practical and reliable.

SELF-SUFFICIENCY IN THE DOMAIN FOOD

Achieving full food self-sufficiency is space-intensive and often unfeasible in densely populated urban areas. In rural settings, however, extensive self-sufficient food systems can be realized due to the availability of land for agriculture and livestock. In urban areas, self-sufficiency is typically limited to small-scale production, such as vegetable gardens, vertical farming, and aquaponics systems. While these solutions can contribute to local food production, they are insufficient to fully meet the nutritional needs of residents in a compact urban environment. Therefore, urban self-sufficiency often relies on a hybrid approach, combining local production with partnerships to source seasonal and sustainable food from nearby regions.

In conclusion, while progress toward self-sufficiency is possible in each domain, existing policies, technical limitations, and spatial constraints present significant challenges. Overcoming these barriers will require innovative solutions alongside supportive regulatory frameworks that enable more decentralized approaches.

5. CONCLUSIONS

Having studied the historical functionality of forts, their modern purposes, and contemporary projects, we have identified numerous systems that can contribute to designing buildings with a high level of self-sufficiency. By combining the best practices and systems from these examples, it is possible to conceptualize a building with exceptional self-sufficient and climate-resilient qualities. However, achieving full self-sufficiency remains challenging due to several factors:

- **Water**: Reusing (waste)water safely continues to pose technical and regulatory challenges.
- **Energy**: Storage technology is still a significant hurdle. Current systems, such as batteries, rely on critical materials and have limited lifespans.
- **Food**: Providing sufficient space for food production to meet demand is not always feasible.

However, advancements in technology may address these limitations in the future, making full self-sufficiency achievable. Anyway, it is crucial to address the domains of water, energy, and food holistically, as they collectively enable a building to function as a closed system.

DESIGN PRINCIPLES FOR THE FORTS OF THE FUTURE

To create self-sufficient, climate-resilient buildings, the following principles should guide the design:

SELF-PROVIDING	Climate Resilience	Integration with Environment	Passive & Active Techniques	Communal living	Recreation	Health & well-being
A building that can provide for the needs for energy, water and partly food of the residents.	A building that withstands external climate influences while reducing impact on its surrounding.	A building that works together with the surrounding landscape.	A building that uses passive techniques to minimize the energy demand and integrates active systems to meet remaining needs.	A building where its residents share spaces and responsibilities, to cultivate connection.	A building where people can recreate and connect with nature.	A building that enhances the health and well-being of its residents.

STRATEGIES FOR SELF-SUFFICIENT AND CLIMATE-RESILIENT BUILDINGS

The following strategies and technologies are crucial for designing self-sufficient, climate-resilient buildings:

Passive Systems	Leverage thermal mass, natural ventilation, daylighting, solar gains, orientation and the natural surroundings.
Natural Elements	Harness natural circumstances like solar, wind, and water reduce demands and reliance on external resources.
Green and Blue Infrastructure	Use vegetation and water for insulation, cooling, and biodiversity
Demand Reduction	Minimize energy, water, and food requirements through efficient design and resource-conscious systems.
Insulation and Materials	Prioritize well-insulated buildings and sustainable, durable materials.
Circular Systems	Close resource loops by turning waste into input for other domains (e.g., using organic waste for biogas or compost).
Active Systems	Supplement remaining needs with technologies like solar panels, heat pumps, batteries, and water purification systems

By integrating these principles and techniques, it is possible to design buildings that achieve high levels of self-sufficiency and climate resilience. These buildings can serve as models for future development, promoting sustainability and adaptability in the face of environmental challenges.

6. APPLICABILITY TO PROJECT LOCATION UTRECHT

UTRECHT AND THE WATERLINE

Utrecht holds a significant place in the history of the Dutch Waterlines, with three major waterlines passing through the province: the Old and New Dutch Waterlines, and the Grebbelinie. The area is surrounded by numerous historic forts, including the analysed Fort Honswijk, underscoring its deep connection to this heritage.

CURRENT DAY CHALLENGES OF UTRECHT

Modern challenges such as water overload, water scarcity, and an overburdened energy network, highlighted in the introduction, are particularly relevant to Utrecht. The region is particularly vulnerable to issues like heavy rainfall, potential droughts, and energy network congestion. These challenges make it crucial for new building projects to be both climate-resilient and future-proof.

THE CHOSEN PROJECT LOCATION: MERWEDE

Utrecht offers a unique chance to bridge historical lessons with contemporary needs. The chosen project location, Merwede, a former industrial area, is set to transform into a healthy, sustainable, and climate-adaptive urban district. This redevelopment aims to create a testing ground for innovations in climate adaptation, health, energy, circular systems, and biodiversity. As such, Merwede is an ideal setting for exploring and applying the principles of self-sufficient, climate resilient design.

References

1. Okwandu, A.C., Akande, D.O. and Nwokediegwu, Z.Q.S. (2024) 'Sustainable Architecture: Envisioning Self-sustaining Buildings for the Future,' *International Journal of Management & Entrepreneurship Research*, 6(5), pp. 1512–1532. https://doi.org/10.51594/ijmer.v6i5.1098.
2. Andrić, I., Koc, M. and Al-Ghamdi, S.G. (2019) 'A Review of Climate Change Implications for Built Environment: Impacts, Mitigation Measures and Associated Challenges in Developed and Developing Countries,' *Journal of Cleaner Production*, 211, pp. 83–102. https://doi.org/10.1016/j.jclepro.2018.11.128.
3. Sandhu, M. and Thakur, T. (2014) Issues, challenges, causes, impacts and utilization of renewable energy sources - Grid integration, International Journal of Engineering Research and Applications. journal-article Vol. 4, Issue 3, pp. 636–643. https://www.ijera.com/papers/Vol4_issue3/Version%201/DH4301636643.pdf.
4. Skalamera, M. (2023) 'The Geopolitics of Energy After the Invasion of Ukraine,' *The Washington Quarterly*, 46(1), pp. 7–24. https://doi.org/10.1080/0163660x.2023.2190632.
5. Steenbergen *et al.* (2009) *Atlas Nieuwe Hollandse Waterlinie*. 010 Publishers.
6. KNMI (2023) *KNMI'23-klimaatscenario's*. https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s.
7. Netbeheer Nederland (2019) Basisinformatie Over Energie-infrastructuur, Regionale Energie Strategieën. https://www.netbeheernederland.nl/sites/default/files/Basisdocument_over_energie-infrastructuur_%2528oktober_2019%2529_161.pdf.
8. Javan, K. et al. (2024) 'A review of interconnected challenges in the water–energy–food nexus: Urban pollution perspective towards sustainable development,' Science of the Total Environment, Volume 912. https://www.sciencedirect.com/science/article/pii/S0048969723079494.
9. Hollandse Waterlinies (2023) Zo werken de Hollandse Waterlinies. https://www.hollandsewaterlinies.nl/nl/ontdek-het-verhaal/geschiedenis/zo-werkt-de-linie.
10. Steenbergen et al. (2009) Atlas Nieuwe Hollandse Waterlinie. 010 Publishers.
11. Hamberg, R. and Ros, R. (no date) Hoe werken de waterlinies? https://www.kenniscentrumwaterlinies.nl/kennis/hollandse-waterlinies/19-hoe-werken-de-waterlinies.
12. Marquez, T. (2023) Climate-resilient buildings are the way forward for finance, architects, and engineers. https://worldgbc.org/article/climate-resilient-buildings-are-the-way-forward/.
13. UNEP and SEfficiency (2021) A Practical Guide to Climate-resilient Buildings & Communities, UNEP. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/36405/Adapbuild.pdf.
14. McDade, E. et al. (2020) A decarbonization framework for planning, landscape, and infrastructure. https://www.architecture2030.org/wp-content/uploads/Decarbonization-Framework-for-Planning-Landscape-and-Infrastructure.pdf.
15. Harlaar, T., Kwant, M., and Stichting Liniebreed Ondernemen (2015) Groene Forten, GROENE FORTEN. Edited by J. Van Niekerk, F. Bosscher, and T. De Zeeuw. https://www.staatsbosbeheer.nl/-/media/10-wat-we-doen/monumenten/201505-brochure-groene-forten.pdf.
16. Klip, H. (2023) Eigen waterzuivering op Forteiland Pampus. https://www.h2owaternetwerk.nl/h2o-actueel/eigen-waterzuivering-op-forteiland-pampus#:~:text=Forteiland%20Pampus%20heeft%20nu%20zijn,membranen%20en%20UV%2DC%20licht.
17. Schoonschip (no date) Schoonschip – Amsterdam. https://schoonschipamsterdam.org/.
18. Greenprint Schoonschip (no date). https://greenprint.schoonschipamsterdam.org/.
19. OZ Architects (2019) Four Elements Hotel | Amsterdam. https://ozarchitect.nl/four-elements-hotel-amsterdam/.

20. Smith, A. (2019) Force of nature – naturally ventilating Amsterdam's Breeze Hotel. https://www.cibsejournal.com/case-studies/force-of-nature-naturally-ventilating-amsterdams-breeze-hotel/.
21. De Ingenieur (2019) 'Sustainable Amsterdam hotel capitalizes on the sun,' 12 April. https://deingenieur.nl/artikelen/sustainable-amsterdam-hotel-capitalizes-on-the-sun.
22. Équipe (no date) Proyecto Roble. https://www.equipeamsterdam.nl/proyecto-roble.
23. Van Helvoirt Groenprojecten (no date) Duurzaam pand én innovatief co-creatieproces. https://www.vanhelvoirtgroenprojecten.nl/over-ons/duurzaam-kantoor/duurzaam-pand-en-innovatief-co-creatieproces.
24. Frearson, A. (2019) 'Floating Farm in Rotterdam is now home to 32 cows,' Dezeen, 10 July. https://www.dezeen.com/2019/05/24/floating-farm-rotterdam-climate-change-cows-dairy/.
25. Goldsmith (2023) FLOATING FARM DAIRY. https://goldsmith.company/floating-farm-dairy/.
26. Dogan, R. (2024) How can floating farms revolutionize urban agriculture in Rotterdam? https://parametric-architecture.com/how-can-floating-farms-revolutionize-urban-agriculture-in-rotterdam/.
27. Effekt (2016) ReGen villages. https://www.effekt.dk/regenvillages.
28. Bosschaert, T. (2022) ReGen Villages Oosterwold. https://except.eco/nl/projects/regen-villages-oosterwold/.
29. Bertelkamp, C. et al. (2018) Regenwater als bron voor drinkwater in Nederland: een haalbare kaart? https://www.h2owaternetwerk.nl/vakartikelen/regenwater-als-bron-voor-drinkwater-in-nederland-een-haalbare-kaart.
30. Jorritsma, M. (2024) Regenwater als bron voor drinkwater, goed idee? https://www.drinkwaterplatform.nl/regenwater-als-bron-drinkwater/#:~:text=In%20principe%20mag%20een%20consument,Dat%20moet%20je%20zelf%20weten.
31. Lokale wet- en regelgeving (2022) Riolering en Water Programma – RWP 2023-2028. https://lokaleregelgeving.overheid.nl/CVDR686166.