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D8.2 – DEVELOPING DESIGN METHODS FOR SUPPORTING THE BUILT ENVIRONMENT RESILIENCE ACCOUNTING FOR SUPPLY CHAINS

APPLICATION TO A REAL DEMO CASE

September 2025 | KTH

MULTICLIMACT

D8.2 – DEVELOPING DESIGN METHODS FOR SUPPORTING THE BUILT ENVIRONMENT RESILIENCE ACCOUNTING FOR SUPPLY CHAINS

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Lead beneficiary	KTH Royal Institute of Technology
Main Authors	Luca Urciuoli (KTH)
Main contributors	Ari Prasetia (KTH), Margarita Golemi (NCSRD)
Reviewers	Mina Moayyedi (UKA), Hijratullah Sharifzada (UMINHO), Sabrina Hafdhallah (RINA-C), Celina Solari (RINA-C)
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Version	Date	What
0.1	15/01/2025	Table of Contents outlined
0.2	01/02/2025	Analysis of pipeline drawings
0.3	02/03/2025	Initial raw materials analysis
0.4	22/04/2025	Tier I Analysis integrated
0.5	15/05/2025	Tier II Analysis
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0.8	31/08/2025	Pre-final version ready for coordinator quality check (Integration of reviewers' comments)
1.0	20/09/2025	Final Version ready for submission

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
BCM	Billion Cubic Meters
BIM	Building Information Modeling
BoM	Bill of Materials
BPD	Barrels per Day
CI	Confidence Interval
CNC	Computer Numerical Control
COSMO CLM	Consortium for Small-scale Modeling – Climate Limited-area Modeling
CW614N	C: Copper alloy, W: Wrought product (as opposed to cast), 614N: Specific alloy number in the EN standard system
CW617N	C: Copper alloy, W: Wrought product (as opposed to cast), 617N: Specific alloy number in the EN standard system
DE	Direct Extraction
DJF	December, January and February
DMC	Direct Material Consumption
DMI	Direct Material Input
EPDM	Ethylene Propylene Diene Monomer
ERA5	European centre for medium-range weather forecasts Reanalysis 5th generation
FSRU	Floating Storage Regasification Unit
ft	feet

JJA	June, July, August
LPG	Liquified Petroleum Gas
MAM	March, April, May
MFA	Material Flow Analysis
OBS	Observed
PA-GF	Glass fiber-reinforced polyamide (PA-GF)
PA6	Polyamide 6
PA66	Polyamide 66
PTB	Physical Trade Balance
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
SARIMA	Seasonal Autoregressive Integrated Moving Average
SD	Standard Deviation
SON	September, October, November
Terra-Urb	Land surface scheme from Cosmo CLM including urban canopy parametrization

Executive Summary

This deliverable (D8.2) provides a detailed assessment of supply chain resilience and sustainability for the Uponor heating solution to be deployed in Riga, Latvia, under the MULTICLIMACT project. The analysis focuses on three core components—Pipe Plus, manifolds, and cabinets, tracing their raw material origins, manufacturing processes, and logistical pathways across Tier I to Tier V suppliers in Ireland, Sweden, and Germany.

The development of Deliverable D8.2 was led by KTH Royal Institute of Technology, which contributed to the core methodology for climate analysis, supply chain mapping, transport infrastructure assessment, and resilience modeling. Demokritos provided specialized expertise in raw material analysis, particularly for plastics and metals used in Uponor's components. REA supported the integration of local data from Riga, including infrastructure and pavilion specifications. Uponor, as the industrial partner, supplied the design specifications and Bill of Materials (BoM) for the heating solution. Together, these partners formed a multidisciplinary team that combined academic research, industrial insight, and regional data to produce a robust and scalable framework for supply chain resilience in the built environment.

To visualize the complexity and interdependencies of these networks, the report includes multi-tier supply chain maps (Figures 14–17). These maps illustrate the flow of materials from upstream sources (e.g., crude oil, ethylene, steel) through intermediate manufacturing stages to final delivery in Riga. They highlight key nodes, such as the Hassfurt facility, which serves as a bottleneck for both manifold and cabinet production, and show how multiple European suppliers contribute to pipeline provisioning, enhancing resilience through redundancy.

Using Material Flow Analysis (MFA) indicators—Domestic Material Input (DMI), Domestic Material Consumption (DMC), and Physical Trade Balance (PTB)—the study evaluates supply risk and resource dependency. Network theory metrics, including betweenness and eigenvector centrality (Figures 19–20), identify critical nodes and chokepoints, offering insights into systemic vulnerabilities and strategic leverage points.

A long-term demand forecast (2035–2075) models a 1% annual growth rate, informing warehousing and distribution needs. The analysis estimates increasing material volumes and CO_2 emissions, with total transport-related emissions projected to reach 14 394 kg CO_2 over four decades. Storage strategies are compared with a recommendation to invest in warehouse infrastructure for long-term scalability and operational continuity.

The supply chain demonstrates moderate resilience through geographic diversification of pipeline suppliers and the potential for ethylene substitution via natural gas. However, critical vulnerabilities remain—particularly the reliance on fossil-based inputs and the centrality of the Hassfurt facility. The network analysis confirms that disruptions to key materials like PVC resin, PA-GF, and steel could cascade through the system. To mitigate these risks, the report recommends strategic supplier contracts, modular design flexibility, and investment in alternative feedstocks. These measures will enhance the supply chain's ability to absorb shocks, maintain continuity, and support scalable deployment across Riga's urban infrastructure.

Integration with Building Information Modeling (BIM) enables scenario planning, sustainability assessments, and resilience modeling within a unified digital framework. This supports smarter urban development and infrastructure that is both future-proof and responsive to global challenges.

1 INTRODUCTION

Efficient and resilient supply chains play a critical role in modern industrial ecosystems, ensuring smooth operations, sustainability, and adaptability in a rapidly evolving global landscape. This report provides a comprehensive analysis of supply and demand dynamics, climate and infrastructure considerations, and the resilience of supply chains within the context of critical components such as pipes, manifolds, and cabinets.

1.1 PURPOSE AND TARGET GROUP

The primary objective of this report is to assess and map the various elements of the supply chain that contribute to the efficient transport and distribution of key materials. By analyzing supply chain structures, raw material dependencies, and transportation hubs, this document aims to provide strategic insights for stakeholders, including manufacturers, logistics providers, policymakers, and sustainability experts, who seek to optimize operations and mitigate risks.

1.2 CONTRIBUTIONS OF PARTNERS

This study is the result of contributions from partners allocated in task 8.2. KTH has developed the main approach, together with analysis of climate, supply chains, transport infrastructure and routes, and the modelling of resilience and sustainability. Demokritos, who have provided valuable expertise in the raw materials analysis for plastics and metals necessary for selected components of the Uponor installation. Table 1 depicts the main contributions from project partners in the development of this deliverable.

Table 1: Consortium partners contributions to D8.2.

PARTNER SHORT NAME	CONTRIBUTIONS
KTH	climate, supply chains, transport infrastructure and routes, and the modelling of resilience and sustainability
NCSRD	Raw materials analysis
REA	Riga data: GEO data and diary pavilion
Uponor	Design and BoM of the solution

2 OBJECTIVES AND EXPECTED IMPACT

In today's rapidly evolving built environment, ensuring the resilience and sustainability of supply chains is critical to mitigating disruptions and fostering long-term efficiency. This task 8.2 and corresponding deliverable contribute to this objective by applying advanced design methodologies in a real-world demonstration case, specifically within the Latvian urban context. By integrating strategic planning tools and sustainability-focused approaches, this initiative strengthens supply chain adaptability and enhances climate-proofing measures.

2.1 OBJECTIVES

The primary objective of this task is to support built environment resilience by developing climate-proof and sustainable supply chains tailored to real-world applications, particularly in the Latvian demo case. This will be achieved through the refinement and practical implementation of the design methods previously explored in Task 2.2. This design methods can be summarized in a framework involving the evaluation of climate-induced demand for renovation within urban settings and calculating material flow requirements across multiple scales, from individual buildings to cities, regions, and entire nations. The supply-side analysis emphasizes the identification of local and external resources to be matched with the demand. The resilience aspects need to consider the robustness of the supply chain networks as well as additional uncertainties due to potential disruption in the transport network (see Deliverable 2.2 Planning and designing methods for supporting the built environment resilience by accurately accounting for supply chains).

To accomplish this, the task focuses on the following key objectives:

- **Application of T2.2 design method to the Riga case**
    - The theoretical framework is applied to the case of Riga, with particular focus on building, city, and territorial scales.
    - Ensure the robustness and adaptability of the planned interventions across different urban levels.
- **Evaluation and development of resilient and sustainable Supply Chains**
    - Design supply chains that can withstand disruptions and respond efficiently to climate variability and external shocks.
    - Incorporate sustainability as a core principle, ensuring resource efficiency and minimized environmental impact.
    - Demonstrate how tactical strategies like optimal aggregation and local storage configurations may enhance supply chain efficiency and responsiveness.
- **Material and Technological Demand Assessment**
    - Identify and analyse key technologies and corresponding materials required for construction and infrastructure resilience, particularly in the Latvian demonstration project.
- **Integration with Advanced Planning Tools**
    - Explain compatibility with Building Information Modeling (BIM) systems for better planning and execution.

2.2 EXPECTED IMPACT

The successful implementation of this task will lead to significant improvements in the resilience and sustainability of supply chains within the built environment, particularly in Riga and Latvia. These impacts will extend beyond theoretical research, contributing to practical applications that enhance urban and territorial planning, climate adaptation strategies, and material management. The expected impacts can be categorized as follows:

1. **Strengthened Built Environment Resilience**
   - Improved adaptability of supply chains to external shocks, such as climate change and geopolitical disruptions.
   - Enhanced robustness of supply networks at multiple scales, ensuring long-term stability for urban development.
2. **Optimized Supply Chain Management and Efficiency**
   - More precise forecasting of material demand, minimizing waste and inefficiencies in logistics and infrastructure projects.
   - Development of localized storage strategies, reducing dependency on external supply chains and improving responsiveness to demand fluctuations.
3. **Enhanced Climate Adaptation and Sustainability**
   - Integration of sustainable materials and technologies into the Latvian demo project, reducing the environmental footprint of construction and infrastructure development.
   - Implementation of climate-proof strategies, ensuring supply chains remain functional even in extreme weather conditions.
4. **Improved Decision-Making and Planning Tools**
   - Facilitating data driven intervention through dedicated BIM-based urban planning platforms.
   - Creation of a scalable methodology that can be adapted to other cities and regions, fostering knowledge transfer and policy advancements.
5. **Broader Economic and Social Benefits**
   - Strengthened local industries by prioritizing regional supply chains and reducing reliance on international suppliers.
   - Enhanced collaboration among stakeholders
   - Policymakers can leverage insights from this project to develop **risk-mitigation policies** that strengthen urban infrastructure.

3 OVERALL APPROACH

3.1 DATA COLLECTION AND ANALYSIS

3.1.1 CLIMATE DATA

In this study, we employ the ERA5@2 km dataset, a dynamically downscaled, convection-permitting reanalysis product [1]. The underlying ERA5 fields are downscaled using the COSMO-CLM regional climate model [2], with the TERRA-URB urban-parameterization module activated [3] to explicitly represent urban land-surface processes such as modified albedo, roughness, and evapotranspiration. Hourly total precipitation amounts are provided on a 0.02° grid, resolving convective-scale storm cells that are critical for accurate pluvial flood hazard modelling in densely built environments. Validation against urban-scale gauge networks and radar composites demonstrates that ERA5@2 km captures both the spatial localization and the peak intensity of extreme hourly rainfall events more faithfully than its parent ERA5 product or coarser statistical-downscaling approaches. This high-resolution precipitation timeseries underpins our hydrodynamic simulations of surface inundation, sewer surcharge, and associated economic loss estimation under design-storm and extreme-return-period scenarios.

Concurrently, the dataset supplies hourly 2 m air temperature fields at the same 2.2 km resolution, enabling detailed characterization of urban heat island amplification and heatwave dynamics across multiple metropolitan morphologies. The dynamically downscaled fields resolve fine-scale temperature gradients, particularly nocturnal cooling deficits in urban cores, and provide a more accurate representation of extreme thermal stress than ERA5, which tends to underestimate peak urban temperatures. We leverage these temperature outputs to derive city-scale heatwave indices (e.g., daily maximum and minimum thresholds, heatwave duration) and to drive vulnerability assessments of critical infrastructure, including energy distribution networks and transport corridors. All data are freely available under a Creative Commons Attribution 4.0 International license.

To assess how extreme climate patterns translate into concrete threats for Riga's built environment, we spatially overlay the hourly ERA5@2 km temperature and precipitation fields onto the OpenStreetMap-derived building footprints from GEO RĪGA [4]. We assign climate values to each footprint via bilinear interpolation of the four nearest ERA5@2 km grid points, preserving sub-grid variability across the 2.2 km cells. This yields for every polygon a continuous time series of rainfall intensity ($m\ h^{-1}$) and 2 m air temperature (K). We then derive two building-level exposure metrics: *Flood exposure* as the count of hours with rainfall intensity above the 95th percentile of all hourly values (1989–2018) and *Heatwave exposure* as the count of days whose daily maximum temperature exceeds the 90th percentile threshold.

3.1.2 COLLECTION OF DRAWINGS

A preliminary drawing was collected in February 2025. This drawing consisted of the initial plan for the pipeline installation, Underfloor Heating & Feed pipes MLC Classic 16x2,0 mm, in the Riga milk and dairy pavilion, v4, scale 1:100. In this drawing 9 floor heating zones are identified.

The installation consists of 28 components: excluding circulating pumps (to help the water circulating in the pipes) and solar panels (to power the pumps with electricity transformed from solar energy). The pipes are connected to Riga district heating system in order to collect hot water and therefore are expected to be used only for heating purposes, i.e., not for cooling.

3.1.3 BILL OF MATERIALS

According to the drawings received, the solution to be installed in the Riga Pavillion is made of 28 components (the full list of components cannot be provided due to confidentiality). 10 of the necessary components were selected for the analysis in this report as shown in the partial BoM in Table 2.

Table 2. Partial BoM showing 10 of 28 components necessary for the solution installation in Riga.

NO	COMPONENT	MEASURE	TYPE	QTY	DIMENSION
1	Uponor Comfort Pipe Plus	16 x 2,0, Coil 640 m	Coils	16 000	Meters
2	Uponor Vario M manifold with flowmeter FM	10 out.	Manifolds	3	Pieces
3	Uponor Vario M manifold with flowmeter FM	11 out.	Manifolds	4	Pieces
4	Uponor Vario M manifold with flowmeter FM	12 out.	Manifolds	4	Pieces
5	Uponor Vario M manifold with flowmeter FM	13 out.	Manifolds	1	Pieces
6	Uponor Vario M manifold with flowmeter FM	14 out.	Manifolds	1	Pieces
7	Uponor Vario M manifold with flowmeter FM	9 out.	Manifolds	3	Pieces
8	Uponor Vario cabinet OW	750x730x135mm	Manifold Cabinets	6	Pieces
9	Uponor Vario cabinet OW	900x730x135mm	Manifold Cabinets	8	Pieces
10	Uponor Vario cabinet OW	1050x730x135mm	Manifold Cabinets	2	Pieces

The main component consists of pipelines totalling 16 000 meters, which are to be connected to six manifolds with different outlets (9 to 14). The manifolds serve as junction points where fluids are collected or distributed. These are equipped with flowmeters to measure fluid rates passing through the pipelines. The manifolds are enclosed into cabinets of three different sizes (Table 2). The cabinets help organize and protect the manifold and connected pipes, ensuring a compact installation while allowing easy access for maintenance (Figure 1).

Figure 1. From left, Uponor Comfort Pipe plus, Manifold 10 outlets, Vario Cabinet 750x730x135mm.[1]

3.1.4 RAW MATERIALS ANALYSIS

To analyse the suppliers for the components necessary to install Uponor's solution, data was collected from Uponor (see previous section, as well as secondary data gathered from searches in google database.

Additional data related to raw materials has been derived from The Global Material Flows Database[2], using the module National 13+ categories material flows. The data has been input in an excel database and analysed accordingly.

For a comprehensive material flow accounting framework, these indicators were included:

Table 3. Classification of types of material flows and derived indicators [5].

INDICATOR	INDICATOR DEFINITION
Domestic extraction (DE)	Domestic extractive pressure on natural resources
Domestic Material Consumption (DMC)	Long-term waste potential
Domestic/Direct Material Input (DMI)	Material requirement of production
Exports (EXP)	Direct exports
Imports (IMP)	Direct imports
Physical trade balance (PTB)	Direct trade dependency

A more thorough explanation of these indicators is given in below:

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[1] http://www.uponor.com

[2] https://www.resourcepanel.org/global-material-flows-database

Table 4. Codes and labels used for the Material Flow Analysis [5].

CODE	LABEL	SEEA-CF TYPE OF FLOW	FORMULA FOR DERIVED INDICATORS
DE	DOMESTIC EXTRACTION	NATURAL INPUT	
IMP	PHYSICAL IMPORTS	PRODUCT	
EXP	PHYSICAL EXPORTS	PRODUCT	
DPO	DOMESTIC PROCESSED OUTPUT	RESIDUAL	
BI_IN	BALANCING ITEMS (INPUT SIDE)	NATURAL INPUT	
BI_OUT	BALANCING ITEMS (OUTPUT SIDE)	RESIDUAL	
DMC	DOMESTIC MATERIAL CONSUMPTION	N.A.	DMC = DE + IMP - EXP
DMI	DIRECT MATERIAL INPUTS	N.A.	DMI = DE + IMP
PTB	PHYSICAL TRADE BALANCE	N.A.	PTB = IMP - EXP
BI	BALANCING ITEMS (NET)	N.A.	BI = BI_IN - BI_OUT
NAS	NET ADDITIONS TO STOCK	N.A.	NAS = DMC + BI_IN - DPO - BI_OUT

Based on known volumes of domestic extraction (DE), physical imports, and exports, important indicators such as direct material input (DMI), domestic material consumption (DMC) and the physical trade balance (PTB) can be calculated:

- **DMI** measures the direct and actual input of materials originating from the natural environment or from the rest of the world, i.e. all materials which are of economic value and available for the national economy's production system. Note that parts of the production system's output are exported. DMI of a given national economy is calculated as the sum of domestic extraction plus physical imports. For individual countries, all imports are considered for the calculation of DMI.
- **DMC** measures the total amount of materials that are directly used in a national economy, i.e. by resident units. DMC is conceptually defined in the same way as other key physical indictors such as e.g. gross inland energy consumption. DMC is the amount of materials that become part of the material stock within the economy or are released back to the environment (DPO). The DMC of a given country's national economy can be calculated as direct material input (DMI) minus physical exports.
- **PTB**, calculated as physical imports minus physical exports, measures the physical trade surplus or physical trade deficit of a given national economy.
- **Domestic Material Input (DMI=DE+IMP):** Best for understanding total supply availability (includes both domestic extraction and imports). If DMI is highly dependent on imports, supply risk increases.

- **Domestic Material Consumption (DMC=DMI-EXP)**: Useful for analyzing demand stability and whether supply is meeting consumption. If DMC grows faster than DMI, there could be future shortages.
- **Physical Trade Balance (PTB=IMP-EXP)**: Best for assessing import dependency. A positive PTB (more imports than exports) means the economy relies on external sources, which makes it vulnerable to supply disruptions.

3.2 SUPPLY CHAIN ANALYSIS

3.2.1 FLOWS ANALYSIS

To evaluate the supply chain flows within the Uponor solution, we conducted a targeted analysis leveraging the Bill of Materials (BoM). Our focus centered on three strategically significant components: Pipe Plus, manifolds, and cabinets. These were selected based on their critical roles in the system architecture and their susceptibility to supply chain disruptions.

Component Dependency Mapping

We began by collecting secondary data to identify and understand the material dependencies associated with each of the three components. This included tracing the origin and flow of raw materials and intermediate goods linked to:

- Pipe Plus
- Manifolds
- Cabinets

We then extended the analysis to the primary manufacturing sites located in Ireland, Sweden, and Germany, which are pivotal in Uponor's production network.

Multi-Tier Supply Chain Mapping

The supply chains were mapped in detail up to Tier V, capturing the extended network of suppliers, sub-suppliers, and logistical pathways. This deep mapping allowed us to visualize the full scope of dependencies and potential vulnerabilities across multiple layers of the supply network.

Volume and Capacity Assessment

Using the supply chain maps, we further analyzed:

- **Material quantities and volumes** required for each component.
- **Import capabilities** of the facilities for sourcing raw materials.
- **Manufacturing capacities** at the respective sites.

Scalability and Warehousing capacity

To complement the supply chain flow analysis of Uponor's solution, we developed a long-term demand projection for the three critical components, Pipe Plus, manifolds, and cabinets, spanning the period from 2035 to 2075. This forecast assumes a steady annual growth rate of 1%, reflecting moderate but consistent expansion in construction activity and infrastructure development.

This sustained growth trajectory necessitates strategic planning for both production scalability and distribution logistics. The growth is discussed in terms of distribution logistics capabilities, examining the warehousing requirements to accommodate the expected growth.

3.2.2 RESILIENCE

To assess the resilience of our supply chains, we conducted a targeted analysis using the BoM, focusing on three critical components. For each component of Uponor's solution, Pipe Plus, manifolds, and cabinets, we performed the following steps:

- **Raw Material Identification.** We mapped out the raw materials required for the production of each component, tracing their origins and supply routes to understand potential bottlenecks or single-source dependencies.
- **Dependency Mapping.** We identified upstream and downstream dependencies, including suppliers, sub-suppliers, and logistical pathways. This helped us visualize the interconnectedness of each component within the broader supply network.
- **Network theory analysis** to discuss the criticality of the supply chain nodes, focusing on the following indicators:

- **Centrality Analysis.** Using network theory, we applied centrality indicators to quantify the influence and vulnerability of each node (material or supplier) in the supply chain:
- **Betweenness Centrality:** Measured how often a node appears on the shortest paths between other nodes, indicating its role as a potential chokepoint.
- **Eigenvector Centrality:** Assessed the relative importance of a node based on its connections to other highly connected nodes, highlighting systemic dependencies.

3.2.3 SUSTAINABILITY

To assess the environmental impact of Uponor's supply chain, we calculated CO_2 emissions associated with the production and distribution of the three key components: Pipe Plus, manifolds, and cabinets. The methodology on transport-related emissions, ensuring a comprehensive footprint analysis. Emissions calculated as:

$$CO_2 emissions = (weight(kg)1000) \times Distance(km) \times CO_2 Factor$$

The factor in the above equation has been set to 0.15 kg CO_2/ton-km, meaning that transporting one metric ton of goods over one kilometre by truck emits approximately 0.15 kilograms of CO_2. For a fully loaded HGV, the emission factor is often around 0.12–0.18 kg CO_2e/ton-km.[3] hence, emissions are computed for the base solution to be installed in Riga's pavilions as well as for the scenario accounting the scalability of the solution across the city (considering 1% annual demand growth).

3 https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F6846a4e6d25e6f6afd4c0180%2Fghg-conversion-factors-2025-condensed-set.xlsx&wdOrigin=BROWSELINK

4 CLIMATE, DEMAND ANALYSIS AND FORECASTING

4.1 RIGA CLIMATE PATTERN

Riga, located on the southeastern coast of the Baltic Sea, experiences a humid continental climate marked by cold winters and mild to warm summers. The city's seasonal cycles are shaped by its high latitude and proximity to the sea, producing a predictable annual rhythm in both temperature and precipitation. Winters are long and dark with persistent cold, while summers are brief but warm, with more frequent precipitation. An analysis of the 1989–2018 hourly record at the grid cell over Riga reveals how this rhythm plays out over each season in terms of average conditions, interannual variability, and long-term trends (Figure 2).

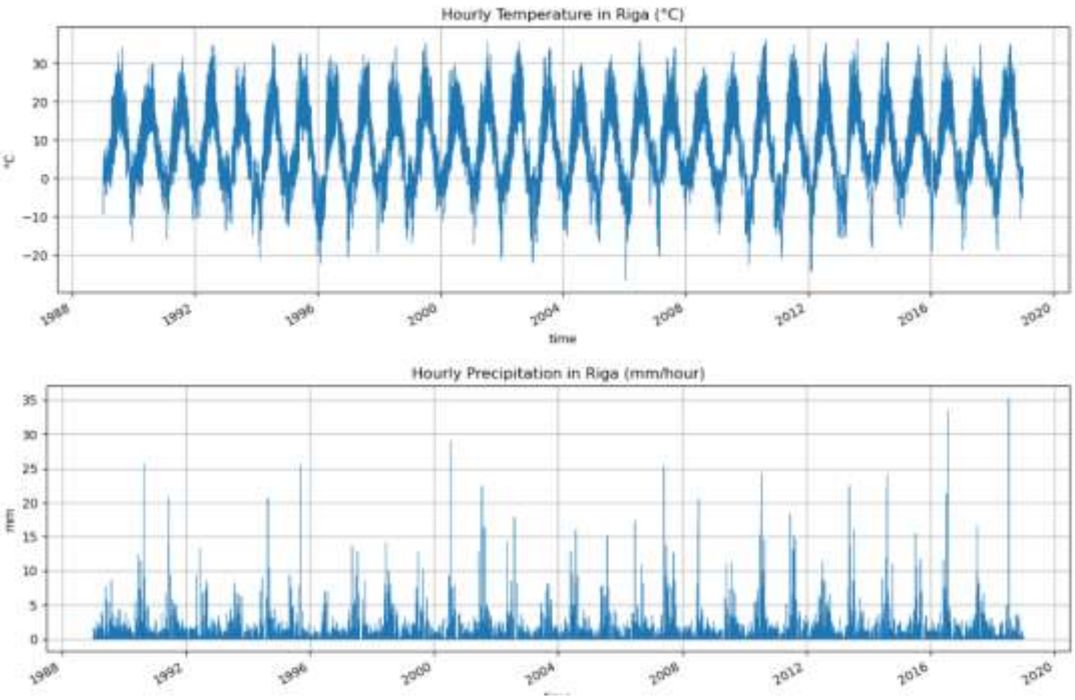

Figure 2. Hourly temperature and precipitation Riga, 1988 – 2020.

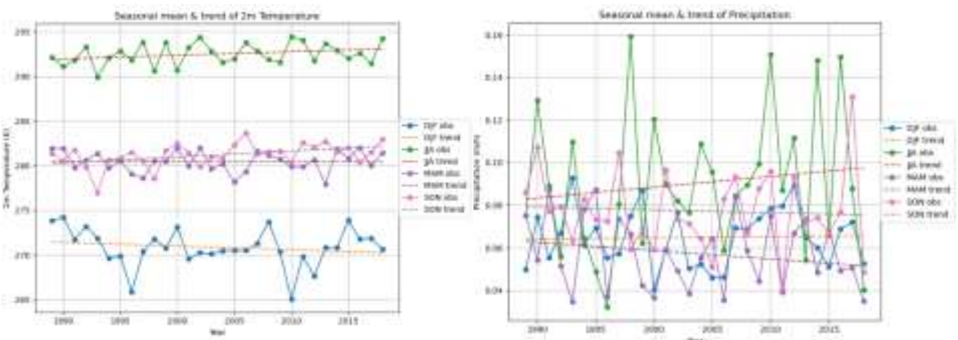

Figure 3. 2m temperature and precipitation, Riga, 1988 – 2020 (left: temperatura, right: precipitation).

Seasonally, Figure 3 shows the pattern plotted against 2m temperature for precipitation in Riga. Winter (December–February) is the coldest season in Riga, with average temperatures ranging between -5 °C and -1 °C (268–272 K). Snow cover and limited sunlight dominate the season, though there is notable variability from year to year. Some winters drop below –8 °C, while others are milder, approaching 1 °C. Despite global warming concerns, the trend for winter temperatures in Riga over the past 30 years appears slightly negative (around –0.02 K per year), but this decline is small and falls within natural variability. This suggests no significant or consistent long-term warming or cooling trend during the winter months.

Spring (March–May) marks a period of transition and rapid warming, with average temperatures increasing to between 5 °C and 8 °C (278–281 K). The snow melts, daylight returns, and precipitation remains moderate, around 0.06–0.07 mm per hour. Interannual variability in spring is moderate; some years bring late frost events in March, while others see early warmth in May. However, long-term trends in spring temperature and precipitation are essentially flat, indicating that the seasonal transition has remained relatively stable over the past three decades.

Summer (June–August) is the warmest and wettest season. Average temperatures typically fall between 19 °C and 22 °C (292–295 K), with some days exceeding 30 °C (303 K). Precipitation peaks during this season, often surpassing 0.10 mm per hour in wetter years. Notably, summer shows the clearest signs of long-term change: there is a statistically significant warming trend of approximately +0.04 K per year, alongside a small but consistent increase in precipitation (+0.001 mm per hour per year). These findings suggest that Riga's summers are becoming gradually hotter and slightly wetter, a trend that may have implications for public health, infrastructure, and water management.

Autumn (September–November) sees a gradual decline in temperature, with seasonal averages between 7 °C and 10 °C (280–283 K). Rainfall levels remain comparable to those in spring, ranging from 0.07 to 0.09 mm per hour. While early autumn can sometimes feel like a late extension of summer, by November, the region is already preparing for winter conditions, with frequent dips below 2 °C. The trends for both temperature and precipitation in autumn are weakly positive, roughly +0.01 K and +0.0007 mm per hour per year, respectively, but lie close to the limits of year-to-year fluctuations. Thus, Riga continues to exhibit a well-defined seasonal climate, with clear distinctions between its cold, dry winters and warm, wetter summers. While spring and autumn have remained relatively stable over recent decades, summer stands out as the season undergoing the most notable changes, with rising temperatures and increasing rainfall. These patterns point to the need for seasonal adaptation strategies, particularly for summer, as the city prepares for potentially more frequent heat events and heavier rainfall in the future.

4.2 FORECAST

The top panel of Figure 4 shows three decades of monthly mean 2 m air temperatures at the Riga grid point. A robust annual cycle dominates, with midsummer highs consistently reaching about 20–23 °C and midwinter lows dipping to -2 °C to -5 °C. Interannual variability around that cycle is modest: most July values fall within a ±1 °C band and most January values within ±1.5 °C. No persistent upward or downward drift is apparent over the 1989–2018 interval, warm and cool years alternate without any clear multi-year trend.

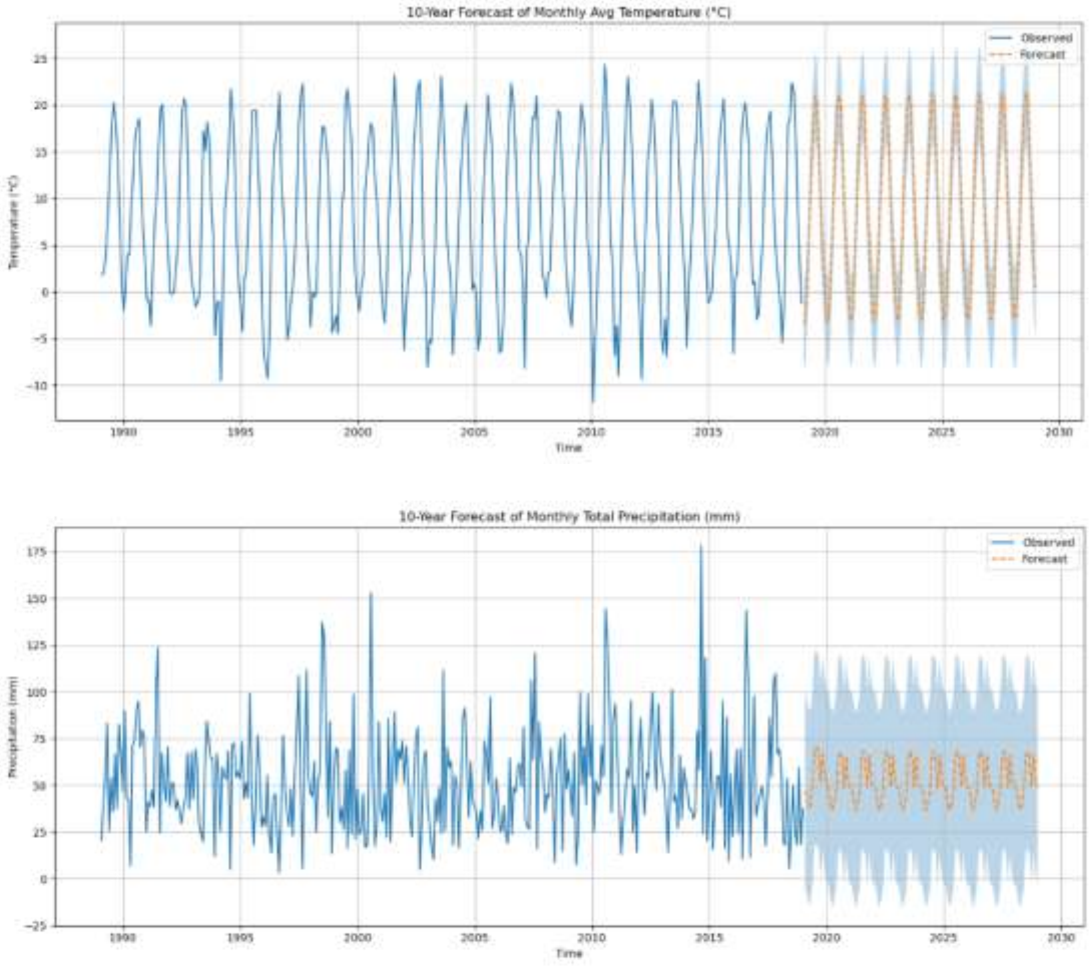

Figure 4. Temperature and precipitation forecast, Riga, 2020 – 2029.

Extending those data forward, the ten-year SARIMA (Seasonal Autoregressive Integrated Moving Average) forecast (dashed orange curve and pale-blue confidence envelope in Figure 4) preserves the historical sine-wave pattern [6], [7]. July means in 2020–2029 cluster around 21–22 °C and January means around –3 °C. Forecast uncertainty grows slowly with lead time: the 95% confidence interval is roughly ±1 °C after one year, widening to about ±2 °C by the end of the decade.

The bottom panel displays the monthly total precipitation record. As expected for this maritime-continental transition zone, there is a pronounced summer maximum (often 70–80 mm month^{-1}) and winter minimum (around 30–40 mm month^{-1}). Superimposed on that template are strong weather-driven spikes, particularly in some summers when totals briefly exceed 150 mm, and occasional very dry winters with totals below 20 mm. No steady trend toward wetter or drier conditions emerges over the thirty-year baseline. Forecasts of monthly precipitation again reproduce the seasonal signature peaks of ≈60–70 mm in midsummer and troughs of ≈20–30 mm in midwinter but with substantial uncertainty reflecting the high year-to-year volatility. The 95% prediction band is about ±10 mm at one-year lead, expanding to ±20 mm by year ten. These projections suggest that Riga’s characteristic cycle of warm, relatively wet summers and cool, drier winters is likely to persist through the 2020s with no dramatic departure from the 1989–2018 climate regime.

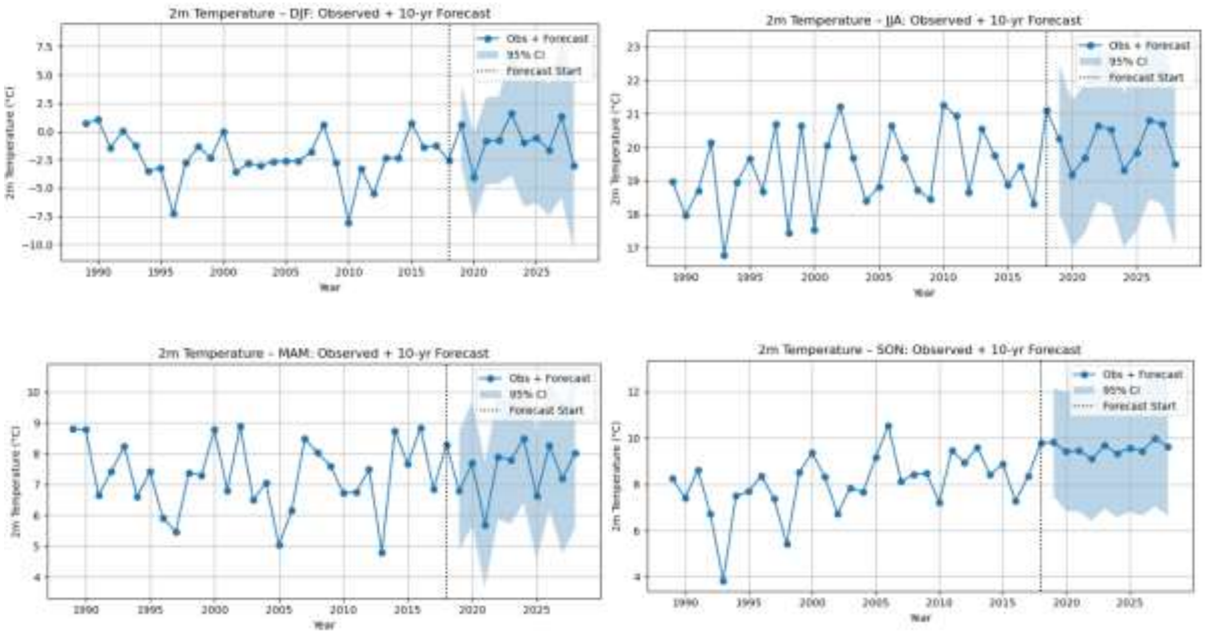

Figure 5. Temperature 10 year forecast, Riga.

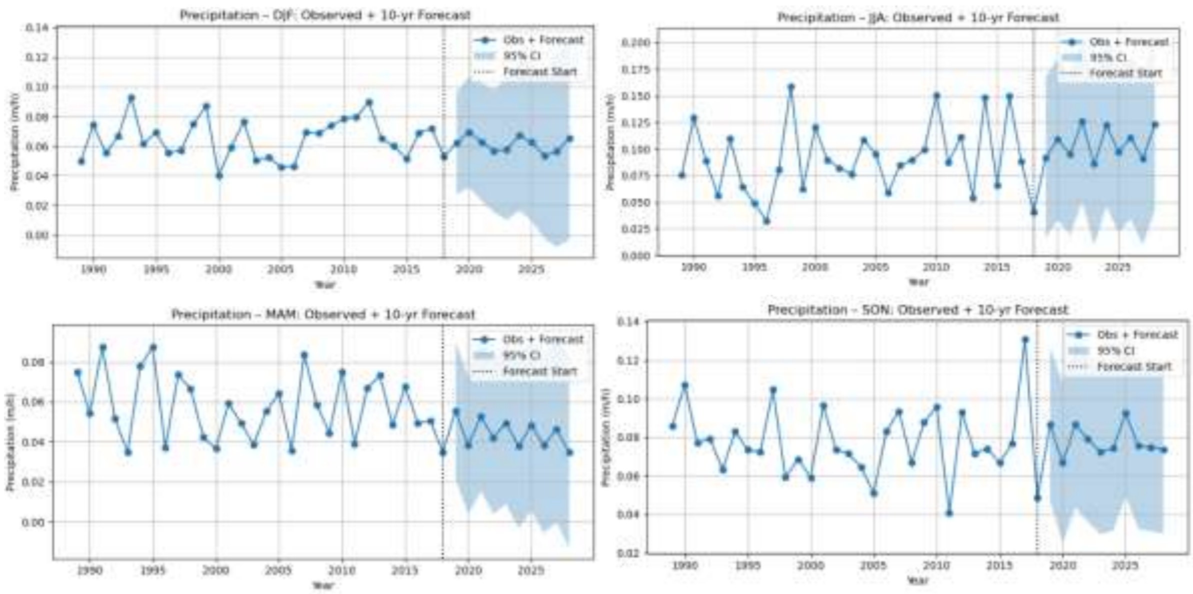

Figure 6. Precipitation 10year forecast Riga.

Over the thirty-year reference period (1988–2017), winter (DJF) precipitation at our Riga site averages about 0.065 m h^{-1} per season, with relatively little year-to-year scatter (standard deviation ≈ 0.014). The fitted linear trend in Figure 6 is essentially flat (+0.001 m h^{-1} per decade) and explains almost none of the variance (R^2 = 0.001). Our ten-year SARIMAX forecast actually nudges the winter mean slightly downward to 0.061 m h^{-1}—a 5.4 % decline relative to historical, though this small change lies well within the wide 95 % confidence bands visible on the DJF precipitation panel. In other words, winter extreme-rain intensities are statistically stable, and supply-chain planners can continue to size off-season drainage assets close to the long-term mean without expecting significant intensification.

By contrast, summer (JJA) precipitation shows both greater variability (historic mean ≈ 0.090 m h^{-1}, SD ≈ 0.034) and an upward trend (+0.005 m h^{-1} per decade, R^2 = 0.018). The forecasted JJA mean of 0.105 m h^{-1} represents a 16.6 % increase over the past three decades' average, consistent with our SARIMAX panel, which shows slightly higher intensities clustering around 2020–2027. Although the trend R^2 remains modest, the combination of higher mean and increased variability means that summer stormwater systems should be designed for significantly greater peak flows than historically experienced, anticipating roughly one-sixth more extreme-rain volume each season.

Spring (MAM) precipitation, in contrast, averaged 0.057 m h^{-1} historically (SD ≈ 0.017) and has trended downward slightly (–0.004 m h^{-1} per decade, R^2 = 0.043). The forecast mean falls to 0.044 m h^{-1}, a 22.6 % drop relative to the baseline. The MAM panel's confidence bands underline the uncertainty, but the negative trend suggests that spring drainage demands may lessen over the coming decade, allowing a modest reallocation of maintenance resources toward summer peak readiness.

Autumn (SON) precipitation sits between spring and summer (historic mean 0.077 m h^{-1}, SD ≈ 0.019) and shows no clear long-term shift (trend ≈ –0.001 per decade, R^2 = 0.004). The forecast mean of 0.078 m h^{-1} is essentially unchanged (+1.1 %), and the SON panel's tight overlap between observation and forecast bands confirms a stable autumn rainfall regime. Turning to 2 m air temperature, winter (DJF) seasonal means have averaged –2.29 °C (SD ≈ 2.11) and actually decline slightly over time (-0.41 °C per decade, R^2 = 0.029). The forecast mean of, 0.84 °C, however, sits more than half a degree warmer than zero and, relative to the historical mean, implies a 63 % change (from a negative baseline). That dramatic "percent change" arises from forecasting toward milder winters, visible in the DJF temperature panel's upward shift after 2017, though the absolute warming is under 1.5 °C per season. Even so, winter mild-spell exposures may increase unseasonal heating-system loads or reduce snow-management requirements.

From the perspective of temperature, seasonally, Summer (JJA) temperatures as shown inFigure 5 average 19.35 °C historically (SD ≈ 1.20) and warm at roughly +0.40 °C per decade (R^2 = 0.087). The SARIMAX forecast mean of 20.05 °C amounts to a 3.6 % increase, consistent with the JJA panel's slight upward offset of the blue dots and the forecast band hovering above the long-term cluster. Although the trend coefficient is modest, even a half-degree of summer warming can meaningfully amplify cooling-load peaks and extend heatwave durations, demanding larger generation reserves.

Spring (MAM) temperatures show almost no long-term trend (historic mean 7.31 °C, SD ≈ 1.15, trend –0.02 °C/decade, R^2 ≈ 0), and the forecast mean of 7.45 °C is only 1.8 % above baseline. The MAM panel similarly shows forecast points drifting only slightly above the cloud of past observations. Finally, autumn (SON) exhibits the strongest warming signal of any season (historic mean 8.07 °C, SD ≈ 1.32, trend +0.67 °C per decade, R^2 = 0.199). The forecast mean of 9.53 °C marks an 18.1 % increase over historical, and the SON panel shows forecast dots tightly clustered near the high end of past variability, indicating that autumn warming may rival summer in terms of seasonal heating of the city.

Our analysis highlights that summer extremes are intensifying, JJA precipitation is projected to be roughly 17 % higher than the historical average, and mean summer temperatures about 3.6 % warmer, while autumn warming is even more pronounced, with SON temperatures forecast at approximately 18 % above baseline despite stable precipitation. Winters are also "milding" significantly in relative terms, with DJF temperatures rising by over 1 °C compared to the cold-season mean, though starting from a low baseline. In contrast, spring remains largely unchanged, indicating that shoulder-season demands will stay near historical levels. For infrastructure and supply-chain planners, these statistics not only signal rising seasonal averages but quantify the magnitude of departures from past norms, critical information for sizing stormwater and energy systems, directing maintenance and staffing resources, and prioritizing risk-mitigation investments across both water and power networks.

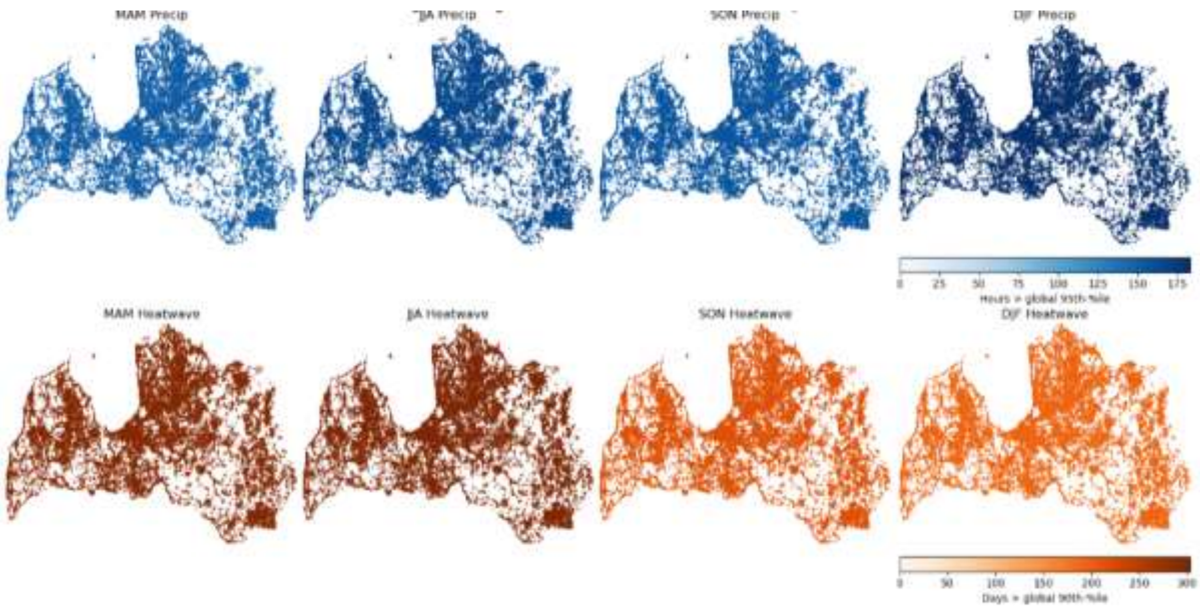

Figure 7. Seasonal distribution of extreme precipitation and heatwave events in Riga. The top row illustrates hours of precipitation exceeding the global 95th percentile for each season (MAM, JJA, SON, DJF), while the bottom row shows days of heatwave events exceeding the global 90th percentile. Color intensity reflects the severity of these events, with darker shades indicating higher values (elaborated from Riga City Council [4]).

Each of these eight panels in Figure 7 maps a single season's extreme-event counts, either the number of hours per season in which rainfall intensity exceeds the global 95th percentile (top row, blues) or the number of heatwave days per season in which daily maximum temperature tops the global 90th percentile (bottom row, oranges), onto the footprints of 677 124 building centroids across Riga. Because we sample via nearest-neighbour lookup, every dot represents one building and its locally experienced extreme-weather count for that season.

In spring (MAM), the spatial pattern of extreme-rain hours (upper left) is relatively uniform, with most buildings seeing on the order of 100–150 high-intensity hours. A handful of clustered hotspots in the city centre and along low-lying river corridors reach toward the upper end of the range (~168 h), suggesting localized convective cells or orographic enhancement near the Daugava banks. By contrast, spring heatwave days (lower left) remain moderate, most buildings record fewer than 150 days above the 90th-percentile threshold, with higher counts concentrated in the southern and western suburbs, where the urban "heat-island" effect is strongest. Moving into summer (JJA), the number of extreme-rainfall hours jumps markedly (upper second panel), with large swaths of the historic core and its immediate periphery experiencing 120–140 convective-storm hours per season. Here the densest clusters, often exceeding 170 h, line major thoroughfares and industrial zones, perhaps reflecting pavement-driven thunderstorm intensification. Summer heatwave days (lower second panel) also peak, with many downtown and inner-city districts seeing 250–300 days above the 90th-percentile daily maximum. This surge underscores the dual challenge of simultaneous stormwater overload and peak cooling demand in JJA.

In autumn (SON), extreme-rain hours taper slightly compared to summer (upper third panel), though large areas still exceed 100 h, especially in the northeast quadrant of the metropolitan area. Seasonal heatwave days (lower third panel) collapse back toward spring-time levels, most sites record 100–200 days, reflecting the rapid decline in continental heat in September and October. Yet persistent warmth in the urban core means that some central neighbourhoods still breach heatwave thresholds well into early autumn. Finally, winter (DJF) (rightmost panels) shows the fewest extreme events of either type. Although intense snowfall and occasional thaws can produce localized runoff bursts, the global 95th-percentile threshold was rarely met, so most buildings register fewer than 100 extreme-rain hours in the cold season. Heatwave-day counts drop off only slightly less dramatically, central districts can still record up to ~300 winter days above the 90th-percentile daily maximum (driven by mid-winter thaw spells), but most suburbs fall below 150 days.

These maps reveal three key insights for urban infrastructure planning (Figure 8):

- **Co-location of Extremes in Summer:** Summer brings both the highest rainfall-exceedance and heatwave counts, often concentrated in the same urban cores. Drainage and cooling systems must therefore be designed to handle concurrent peak loads, stormwater overflow and surges in air-conditioning demand, within the same tight seasonal window.
- **Subseasonal Heterogeneity:** Even within a single season, building-by-building exposure can vary by 20–30 % depending on proximity to water bodies, pavement density, or urban-heat-island intensity. This spatial heterogeneity argues for targeted, neighbourhood-scale interventions, green-roof incentives in hotspots of convective-storm intensity, and passive-cooling retrofits in the areas with the highest heatwave counts.
- **Persistent Low-Season Demand:** Although autumn and winter see far fewer extremes, the nonzero counts, especially of winter heatwave days, highlight that infrastructure cannot fully "stand down" in off-peak months. Maintenance scheduling, pumping-station readiness, and baseline power-supply margins must remain in place year-round, even as resources focus on summer resilience.

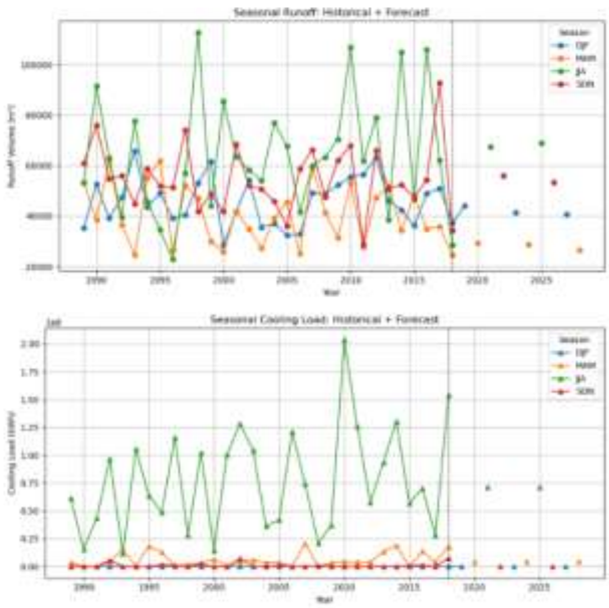

Figure 8. Seasonal runoff and cooling load, historical and forecast, Riga.

Over the historical 30-year period, summers (JJA) regularly yield the greatest volumes of runoff, frequently exceeding 80 000 m^3 per season across the building footprints we studied, while spring (MAM) and autumn (SON) produce moderate volumes and winter (DJF) is predictably quiet. That pronounced summer peak aligns with the meteorological reality that convective, intense thunderstorms dominate in warm months. In a supply-chain context, these volumetric peaks translate directly into "spikes" in demand for stormwater conveyance: stormwater-drain pumping capacity, retention-basin emptying schedules, and maintenance of sewer-trunk lines.

Looking forward, our SARIMAX forecast through 2027 suggests a modest upward drift in summertime runoff, albeit with wide confidence bands that overlap historical highs and lows. That uncertainty implies that supply-chain planners cannot rely on a single "average" summer; they must assume the possibility of extreme seasons, years in which 100 000 m^3 or more of runoff must be captured, treated, or released without overwhelming sewers or natural waterways. From a procurement standpoint, this means maintaining surge capacity in inlet-grate cleaning, scheduling mobile pumps and tankers for rapid deployment, and pre-stocking repair parts for overflow valves and culvert inspections. The "supply" of stormwater–management resources (both capital equipment and operational crews) must be scaled not to mean runoff but to the upper quantiles of forecasted extremes, ideally the 90th or 95th percentile of seasonal volumes.

In contrast to runoff, cooling demand is overwhelmingly a summer phenomenon. Historical JJA cooling loads at our urban site routinely climb above 1×10^8 kWh per season, orders of magnitude higher than spring or autumn, and essentially zero in winter. Those peaks correspond to continental-scale heatwaves (for instance, the 2003, 2010, and 2016 European heat events), during which utilities see simultaneous spikes in residential and commercial air-conditioning use. In the language of supply-chain management, these are "peak-demand events" that stress generation, transmission lines, distribution transformers, and even the upstream fuel or renewable-integration systems.

Our forecast maintains similarly high summer peaks through 2027, suggesting that cooling-demand drivers, namely, the frequency and intensity of heatwave hours, are not abating. For a utility or independent power producer, this means planning for summer "net loads" that could exceed historical highs by 10–20 percent. In practical terms, fuel procurement contracts (natural gas, liquid fuels) must include clauses for higher-than-expected dispatch volumes; renewable developers and grid operators must consider the risk of midday solar peaks coinciding with maximum air-conditioning loads; and battery-storage or demand-response programs should be scaled to shave those summer peak slices to avoid brownouts or expensive peaker-plant dispatch.

Taken together, the joint seasonality of runoff and cooling demand reveals a fundamental complementarity, and tension, within the municipal supply chain: Complementarity: Summer is simultaneously the wettest in terms of intense rainfall and the hottest in terms of heatwaves. A single season therefore carries dual infrastructure burdens: overflowing storm sewers on the one hand, and near-peak electrical loads on the other. Emergency management, therefore, must coordinate crews who clear storm drains and crews who respond to transformer overloads or distribution-circuit trips. Tension: Operational budgets and capital-investment plans are finite. Funds allocated to increase stormwater-management capacity (e.g. upsizing culverts) are dollars not spent on grid modernization (e.g. upgrading substations). Yet both systems face their biggest stresses in the same months. A weather-driven demand analysis that aggregates these seasonal peaks into a unified "resilience challenge" can help city planners and utilities prioritize dual-use investments, such as using stormwater-retention basins as emergency heat-sink reservoirs for district cooling or deploying micro-grids co-located with pump stations to supply their own surge-power needs during heatwaves. By combining historical extremes with a 10-year forecast, we give supply-chain managers a time horizon for budgeting and procurement. In water-infrastructure procurement cycles (often 5–10 years from planning to commissioning), knowing that projected JJA runoff is likely to remain in the 70 000–90

000 m^3 range (with occasional excursions above 100 000 m^3) allows engineers to "right-size" detention-pond volumes and pumping-station capacities. In energy procurement, multi-year power-purchase agreements and capacity-market bids can use forecast cooling loads as baselines, ensuring that generation commitments and demand-response incentives align with near-future peaks.

Such demand-analysis outputs also feed into supply-chain risk assessments: for example, a utility might model the impact of simultaneous extreme rain (causing street floods that impede field-service vehicles) and extreme heat (pushing transformer loads to limits) on repair times and reliability metrics. That integrative view informs not just capital projects but also staffing, cross-training (e.g. enabling water-utility crews to assist grid repairs), and stockpiling of critical spares. Procurement timelines of five to ten years can now be anchored to probabilistic demand profiles rather than simplistic averages, while maintenance schedules can be aligned to the narrow windows when both stormwater and cooling demands hit their annual highs. In this way, our demand analysis becomes more than an academic exercise: it is a decision-support tool that ensures urban systems remain reliable, responsive, and resilient in the face of increasingly extreme seasonal weather.

4.3 HEATING-COOLING DEMAND

Based on the forecasted climate and weather patterns in Riga, there will be a significantly higher demand for energy-saving heating and cooling solutions. The analysis reveals that summer seasons are increasingly marked by simultaneous extremes — intense rainfall and prolonged heatwaves — which place dual stress on urban infrastructure. Cooling demand, in particular, is projected to remain high through 2027, with seasonal loads potentially exceeding historical peaks by 10–20%. This sustained pressure on air-conditioning systems and electrical grids, coupled with subseasonal variability and persistent off-season heatwave days, underscores the need for buildings and utilities to adopt more efficient, resilient energy systems. Passive cooling retrofits, demand-response programs, and smart grid upgrades will be essential to manage peak loads and reduce reliance on fossil-fuel-based plants. In short, the climate trajectory points to a future where energy-saving heating and cooling technologies are not just beneficial — they're critical for maintaining urban reliability and resilience.

The area of interest where the Uponor solution will be installed is located in the city center of Riga. Riga, the capital of Latvia, is situated on the Gulf of Riga at the mouth of the Daugava River, where it meets the Baltic Sea. The city occupies a flat and sandy plain with elevations ranging from just 1 to 10 meters above sea level, covering a total area of approximately 307.17 km^2. As Latvia's largest city, Riga is home to around 591,882 residents in the city proper and 847,162 in the metropolitan area as of 2025. Its historical center, a UNESCO World Heritage Site, is celebrated for its striking Art Nouveau architecture and preserved 19th-century wooden buildings. For geospatial analysis and urban planning, the GEO RĪGA portal offers open access to thematic maps, 3D models, and detailed data on infrastructure, biodiversity, and administrative boundaries.[4]

Riga's urban landscape is enriched by its iconic market pavilions, particularly those of the Riga Central Market, one of Europe's largest and most architecturally unique marketplaces. Opened in 1930, the market spans over 72,300 m^2 and features five massive pavilions, each originally constructed using repurposed metal frameworks from World War I German Zeppelin hangars. These structures blend Art Nouveau, Neoclassicism, and Art Deco styles, and have become a symbol of Riga's architectural ingenuity. The pavilions serve not only as bustling trade hubs with over 3,000 stands, but also as cultural venues hosting tastings, tours, and events. Visitors can explore the underground passages beneath the market—once used for storage and refrigeration—and learn about the site's role during

[4] *https://www.redzet.lv/en/info/Riga*

WWII and the Soviet era. Alongside the Central Market, the Āgenskalns Market also features a historic pavilion, recently renovated and now offering event spaces, guided tours, and local culinary experiences. These pavilions are vital to Riga's cultural and economic fabric, blending heritage with modern urban life.[5]

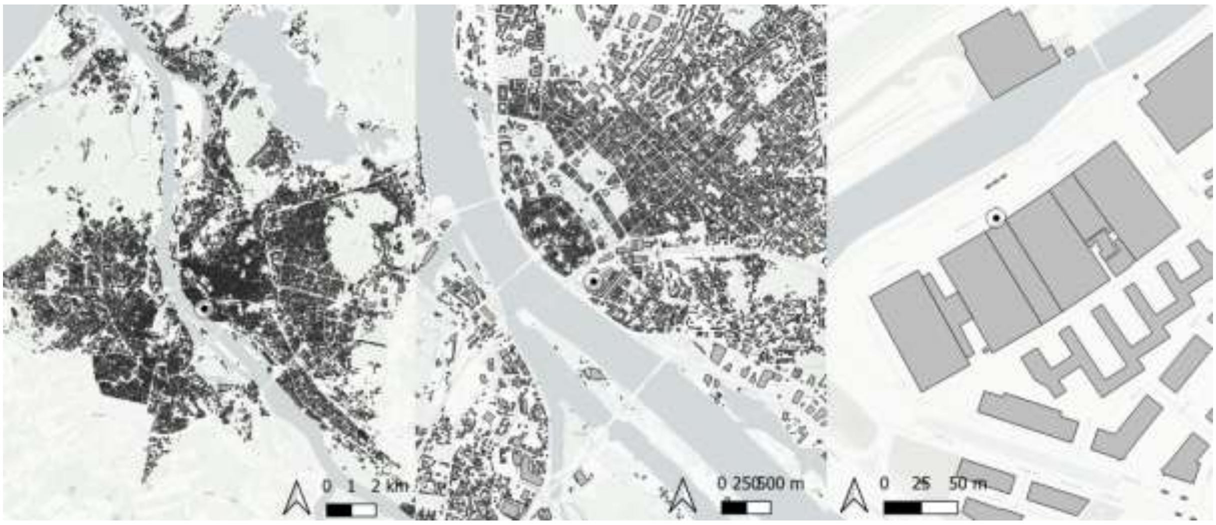

Figure 9. Riga geographic multi-scale view of Riga highlighting the Central Market pavilions.

Based on data extracted from the building layer of Riga, the whole city has a total building surface of 21,100,900 m^2. The pavillions' area is instead approximately 12,916.3 m^2, in total, while the building where the Uponor solution will be installed has an approximate surface of approximately 2756.385 m^2.

Table 5. Estimated demand city of Riga from 2035 to 2065.

YEARS	DEMAND (1%)	DEMAND (2%)	DEMAND (3%)	DEMAND (4%)
2035	211 009.00	422 018.00	633 027.00	844 036.00
2045	213 330.10	430 458.36	652 017.81	877 797.44
2055	215 676.73	439 067.53	671 578.34	912 909.34
2065	218 049.17	447 848.88	691 725.69	949 425.71
2075	220 447.72	456 805.86	712 477.47	987 402.74

To scale the deployment of the Uponor solution across Riga, we model demand growth over a 50-year horizon by assuming a compound increase of 1% to 4% every decade (Table 5). This scenario reflects gradual urban expansion, infrastructure renewal cycles, and rising sustainability targets due to the changing climate / weather conditions. By projecting demand in decadal increments, we will anticipate material and supply chain needs, ensuring that the solution remains adaptable to both conservative and accelerated growth trajectories.

[5] https://en.wikipedia.org/wiki/Riga_Central_Market

Next table, Table 6, expounds the annual demand estimated for the same time period of 50 years, using Table 5 as a reference.

Table 6. Estimated annual demand.

YEARS	DEMAND (1%)	DEMAND (2%)	DEMAND (3%)	DEMAND (4%)
2035-2045	21 100.9	42 201.8	63 302.7	84 403.6
2045-2055	21 333.01	43 045.84	65 201.78	87 779.74
2055-2065	21 567.67	43 906.75	67 157.83	91 290.93
2065-2075	21 804.92	44 784.89	69 172.57	94 942.57

5 MAPPING OF SUPPLY CHAIN AND TRANSPORT INFRASTRUCTURE

5.1 UPONOR PIPE PLUS

5.1.1 SUPPLY CHAIN

Riga construction site will install 16 000 meters of Uponor pipe plus. These pipelines can be supplied by three main locations in Europe:

1. **Germany**, Hassfurt.
2. **Ireland,** Dublin.
3. **Sweden,** Virsbo.

These factories have inbound and outbound storage. In the inbound PVC resin in granular form is stored, together with plasticizers, stabilizers, fillers, lubricants, pigments and other additives.

Table 7. Composition Breakdown of PVC-Based Material A structured overview of key materials used in PVC formulation, highlighting their quantities, percentages, and functional roles in the final product. Quantities and proportions are computed for 1 ton of pipe production.[6]

MATERIAL	QUANTITY (KG)	%	PURPOSE
PVC Resin	~850	85%	Base material
Plasticizers	~50	5%	Provides flexibility
Stabilizers	~20	2%	Prevents degradation
Fillers	~50	5%	Adds strength (e.g., calcium carbonate)
Lubricants	~10	1%	Aids extrusion
Pigments & Other Additives	~20	2%	Enhances color and other properties

The manufacturing processes are the following [8] (Figure 10):

- **Extrusion Process** – The material is heated, melted, and pushed through a die to form the pipe. The machines needed are the following:
    - **Mixer.** High-speed mixer to blend the materials.
    - **Extruder**. It melts and shapes the plastics using a screw mechanism.
    - **Die and molds**. This process shapes the final structure of the pipe.
- **Cooling & Shaping.** The newly formed pipe is cooled to solidify its shape. A water-cooling tank can be used.
- **Cutting & Finishing** – Pipes are cut to the required length and undergo quality checks like pressure testing.

[6] https://www.kviconline.gov.in/pmegp/pmegpweb/docs/commonprojectprofile/PVCPipes.pdf

- **Grinding.** A grinder may be used to recycle excess material for reuse.

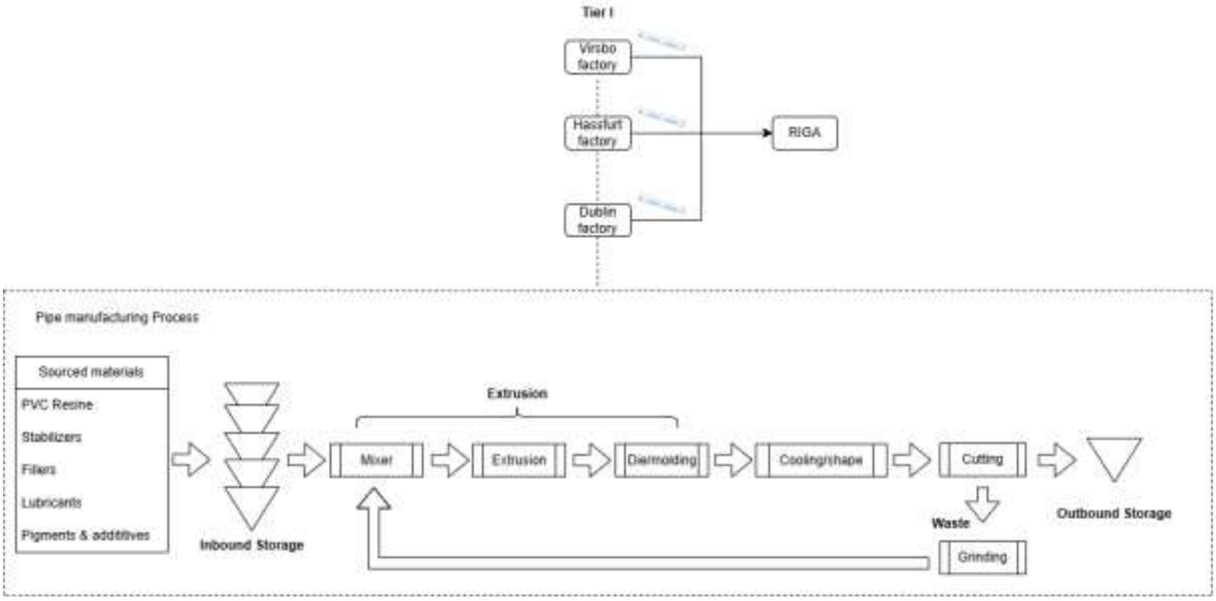

Figure 10. Uponor Tier I suppliers and manufacturing process, adapted from Mezistrano [8].

5.1.2 RAW MATERIALS

Each of the sourced materials used to manufacture the pipelines, need different types of raw materials. We limit the analysis of raw materials necessary for PVC resins since these constitute 85% of the final product. Also, we consider that 1 ton of PVC resin necessitates about 0.5 to 0.6 tons of Ethylene.

The raw materials of interest are the following [9]:

- **Ethylene.** Ethylene is extracted from crude oil or natural gas via cracking. The extraction from crude oil requires a refinery to produce naptha. The naptha is heated with stem in a cracking furnace, forming lighter hydrocarbons like ethylene. When the mix is cooled down the ethylene is isolated from other gases in separation unites, using compression and cryogenic distillation.
- A second option is to extract ethylene from natural gas components like ethane and propane. The process is the same as for crude oil as the ethane is preheated to about 850 °C. At this temperature, ethane breaks into ethylene and propane. Following a rapid quenching the compound is cooled down and ethylene is collected in separate units.
- **Chlorine.** Chlorine comes from NaCl (Sodium Chloride) which is mixed in high concentrations with water, i.e. brine. Brine is purified to remove impurities like calcium and magnesium. Next, it's fed into an electrolytic cell, which contains two electrodes:'
    - Anode (positive electrode), chloride ions are oxidized to form chlorine gas.
    - Cathode (negative electrode), water is reduced to produce hydrogen gas and hydroxide ions.

To understand the capacity of available industries that can produce Ethylene and Chlorine we made an analysis of availability of oil and gas, both as domestically produced in the countries producing PVC resin or imported in these countries.

5.1.2.1 Sweden

Oil and Gas production
Sweden has minimal domestic production of oil and gas:

- **Oil Production:**
    - Sweden produces only about 12 411 barrels per day of oil (as of 2016), ranking #92 globally.[10]
    - It has no significant crude oil reserves and no domestic crude oil production.[11]
    - Most of its oil is refined from imported crude at five refineries with a combined capacity of 454 000 barrels/day.[11]
- **Natural Gas Production:**
    - Sweden does not produce natural gas domestically.
    - It relies entirely on imports, primarily for industrial use and limited heating.

Conversion into Ethylene
Next table shows the main oil crude refineries available in Sweden (Table 8). Based on the available data it is assumed that these refineries can extract ethylene from oil crude based on the process previously described.

Table 8. Main refineries in Sweden converting crude oil in ethylene (BPD = Barrels per day).

REFINERY NAME	LOCATION	CAPACITY (BPD)	OPERATOR	SPECIALTY
Preemraff Lysekil	Lysekil	220 000	Preem AB	Diesel, gasoline, renewables
Preemraff Gothenburg	Gothenburg	78 000	Preem AB	Renewables, lubricants
St1 Refinery	Gothenburg	125 000	St1 Nordic	Sustainable fuels
Nynas Nynäshamn	Nynäshamn	90 000	Nynas AB	Bitumen, specialty oils
Nynas Gothenburg	Gothenburg	N/A	Nynas AB	Specialty oils

Imports
In 2023, Sweden imported approximately 350,000 BPD of crude oil.[12]

- Main countries from where crude oil is imported:
    - Norway
    - Russia
    - Denmark
- Sweden imports 123% of its oil consumption, indicating a strong reliance on foreign oil.[10]

In 2023, Sweden imported $1.26 billion worth of petroleum gas[13]. The main countries exporting petroleum gas to Sweden include:

- Norway ($423M)
- United States ($357M)
- Denmark ($232M)
- Finland and UK also contribute.

Table 9 summarizes the key findings related to Swedish domestic production and imports of oil and gas.

Table 9. Production and imports of oil and gas in Sweden.

CATEGORY	DOMESTIC PRODUCTION	IMPORTS (2023)	MAIN IMPORT SOURCES
Crude Oil	~12 411 barrels/day	~350 000 barrels/day	Norway, Russia, Denmark
Petroleum Gas	None	$1.26 billion	Norway, USA, Denmark, Finland
Natural Gas	None	Included in petroleum gas	Norway, USA, Denmark

Data from the Global material flow database was retrieved in order to show data about plastics consumption, production and trading (Figure 11). Looking at the diagram for Sweden's plastics from fossil fuels, we can interpret several trends that speak to the resilience of its plastics system. Imports of plastics rose steadily until around 2010, suggesting a growing dependence on foreign sources. However, after 2018, there's a noticeable drop in imports, which could indicate a shift toward domestic production, reduced consumption, or improved recycling and circularity. This change is significant because a resilient system typically reduces reliance on external inputs, especially for critical materials like plastics.

Exports, on the other hand, show a gradual increase over time with some fluctuations. This could mean Sweden is exporting more plastic products or plastic waste. If it's the latter, it might point to a vulnerability—outsourcing waste management rather than handling it domestically. That's less resilient, especially if global waste trade regulations tighten.

Domestic material input peaked around 2010 and then declined sharply, mirroring the import trend. This suggests that Sweden may have reduced its overall plastic throughput, possibly due to efficiency gains or a shift in consumption patterns. Domestic material consumption fluctuates without a clear long-term trend, which makes it harder to assess whether Sweden is stabilizing its internal demand or facing volatility.

The physical trade balance isn't labelled directly, but the gap between imports and exports implies that Sweden had a trade deficit in plastics for many years. That means it was importing more than it exported, which can be a sign of vulnerability if those imports are essential and hard to substitute.

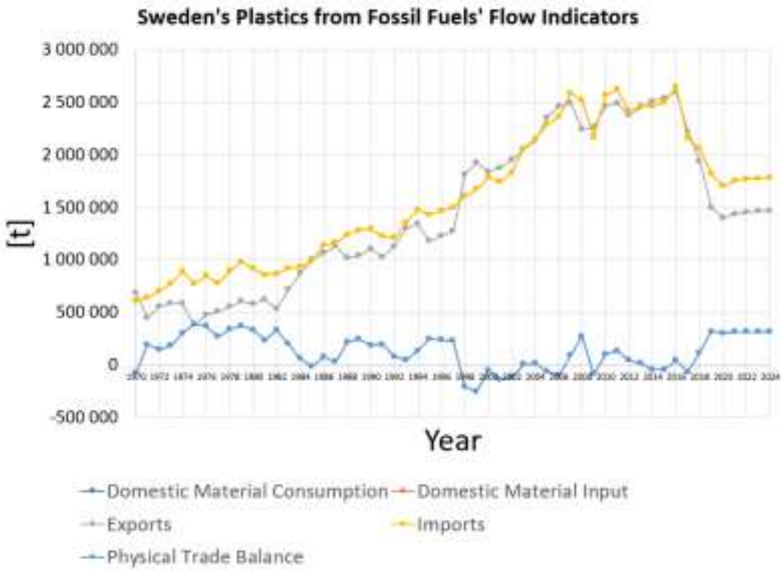

Figure 11. Data about plastics materials in Sweden (author's elaboration from data available from Global Material Flow Database[2]).

Production and Transport Infrastructure

We are interested to understand the main transport infrastructure to replenish the identified industries in Sweden. For oil and gas there are five main terminals in Sweden that can handle the storage of oil crude or gas entering Sweden via sea (Table 10). These terminals can be distinguished into the following types:

- Crude Oil Terminal: Designed to receive and store unrefined oil for processing.
- Refined Products Terminal: Handles gasoline, diesel, jet fuel, and other finished fuels.
- Multipurpose Terminal: Can manage both crude and refined products, often with LPG and chemicals.
- Specialty Oils Terminal: Focused on niche products like bitumen, paraffin, and lubricants.
- Bunker Station: Supplies fuel to ships, often located near busy maritime routes.

Hence, these terminals are directly connected to the refineries identified in Sweden dedicated to the transformation of crude oil into plastics.

Table 10. oil and gas entry points.

IMPORT TERMINAL	LOCATION	LINKED REFINERIES	STORAGE CAPACITY	TERMINAL TYPE
Torshamnen Terminal	Gothenburg	Preemraff Gothenburg, St1, Nynas	~1 million m^3	Crude oil, LPG, refined products, multipurpose
Lysekil Terminal	Lysekil	Preemraff Lysekil	~1.3 million m^3	Crude oil, deepwater, refinery-integrated
Nynäshamn Terminal	Nynäshamn	Nynas Nynäshamn	~1 million m^3	Bitumen, specialty oils, refined products

Gävle Liquid Terminal	Gävle	Regional distribution	~750 000 m^3	Petrol, ethanol, fuel, jet fuel
Malmö Port	Malmö	Regional support	~500 000 m^3 (estimated)	Liquid bulk, refined products, bunker station

Gas, specifically ethane, can also be used in substitution of oil crude to produce ethylene. According to the information retrieved, we found only one terminal that is used in Sweden to store ethane. This is located in Stenungsund with a storage capacity of 52 000 m^3. This consists of a cryogenic full containment tank and a network of pipelines integrated which stores and supply customers with a rate of 625 kilotons/year (approximately 1.1 million m^3).

Table 11. Ethane storage and processing information in Sweden.

FACILITY	LOCATION	STORAGE CAPACITY	TYPE	PURPOSE	PROCESSING CAPACITY
Ethane Terminal	Stenungsund	52 000 m^3	Cryogenic full-containment tank	Storage for ethylene production	N/A
Borealis Steam Cracker	Stenungsund	Pipelines integrated with terminal	Feedstock-flexible cracker	Converts ethane to ethylene	625 kilotons ethylene/year

The Borealis steam cracker can process directly the ethane into ethylene. Some ethylene is likely exported regionally to other facilities in Sweden or Northern Europe, either as raw ethylene or as polyethylene pellets. In addition, Borealis is a major supplier of specialty plastics for global energy, oil, and water infrastructure projects, so products derived from ethylene are shipped internationally.

5.1.2.2 Germany

Crude Oil Production

In 2023 the output of crude oil in Germany was ~1.6 million tons [14]. This amount equals to a 2.2% share of Germany oil's need [15]. Main production facilities are located in the following regions:

- Lower Saxony and Schleswig-Holstein
- Largest field: Heide-Mittelplate I in the Wadden Sea

Natural Gas Production

In 2023 Germany had an output of natural gas of about ~4.3 billion m^3 [14]. *Nevertheless,* production dropped by 10.4% in 2023 [15]. The main region dedicated to the production of gas is the Lower Saxony.

Imports of oil and gas

Germany remains heavily reliant on imports to meet its crude oil and natural gas needs, as domestic production continues to decline. In 2023, Germany imported approximately 77 million tons of crude oil, down from 88 million tons the previous year. This accounted for over 97% of the country's oil consumption, with domestic output covering only a small fraction. The main suppliers of crude oil included Norway, Kazakhstan, and the United States, following the complete cessation of Russian imports due to EU sanctions and Germany's energy policy shift [16].

For natural gas, Germany imported around 90 billion m^3 in 2023, with domestic production contributing only about 4.3 bcm. The country diversified its gas sources significantly after reducing reliance on Russian pipeline gas. Imports now come primarily from Norway, the Netherlands, and LNG shipments from the United States, which have grown rapidly in volume. This shift reflects Germany's broader strategy to enhance energy security and transition toward cleaner alternatives while maintaining stable supply chains [16].

Table 12. Production and imports of oil and gas in Germany.

CATEGORY	DOMESTIC PRODUCTION	IMPORTS (2023)	MAIN IMPORT SOURCES
Crude Oil	~1.6 million tons	~77 million tons (approx.)	Norway, OPEC countries, Kazakhstan
Natural Gas	~4.3 billion m^3	~90 billion m^3 (approx.)	Norway, Netherlands, LNG from USA

Additional data was retrieved from Global Material database, this line graph tracks five key indicators related to Germany's plastic flows derived from fossil fuels, spanning from 1970 to 2024. The vertical axis measures quantities in tons [t], ranging from −10 million to +25 million tons. In this diagram we may notice that DMC and DMI have grown steadily, highlighting increasing domestic demand and input.

The trade balance oscillates, suggesting periods of both surplus and deficit in plastic flows. From a resilience viewpoint, the diagram suggests that Germany could have a high domestic demand for plastic products that isn't met by local production. It could also indicate outsourcing of plastic manufacturing to other countries. Dependence on imports from other countries is typically a sign of vulnerability to global supply chain disruptions (e.g. geopolitics, like tariff and trade wars).

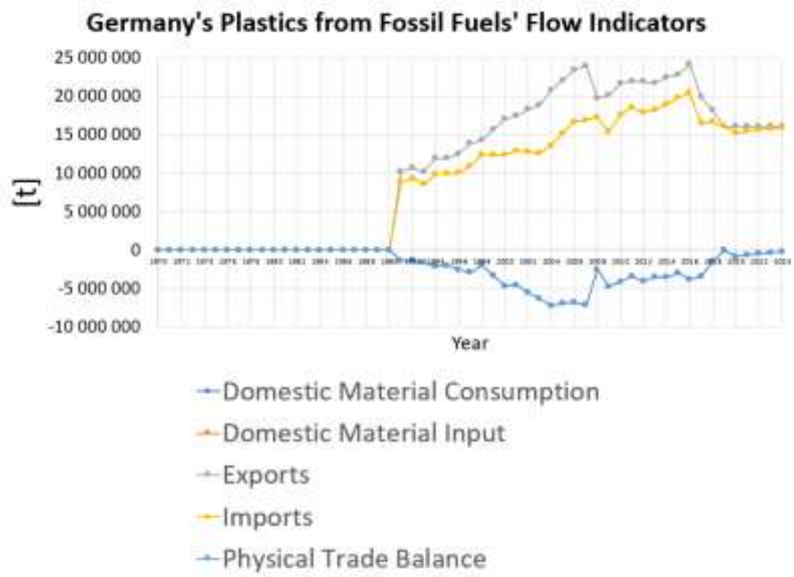

Figure 12. Plastics from fossil fuels, Germany (author's elaboration based on data available from Global Material Flow Database[2]).

Conversion into Ethylene

Germany hosts several major oil refineries that are not only crucial for fuel production but also play a significant role in the petrochemical industry, particularly in the transformation of crude oil into ethylene. Ethylene is a key building block for plastics, solvents, and other industrial chemicals. The table below highlights three prominent refineries that integrate steam cracking or other petrochemical processes to produce ethylene (Table 13):

- Their locations span key industrial regions such as Bavaria and North Rhine-Westphalia.
- Capacities are listed in barrels per day (BPD), reflecting their scale.
- Each refinery is operated by a major energy company with specialized infrastructure for petrochemical output.

These facilities are vital nodes in Germany's chemical supply chain, often linked to larger chemical parks and pipeline networks that distribute ethylene and other feedstocks across Europe.

Table 13. Refineries converting crude oil in Ethylene.

REFINERY NAME	LOCATION	CAPACITY (BPD)	OPERATOR	SPECIALTY
Burghausen Refinery	Burghausen, Bavaria	~75 000	OMV	Petrochemicals: Ethylene, Propylene
BP Gelsenkirchen Complex	Gelsenkirchen, NRW	~265 000	BP Europa SE / BP Gelsenkirchen GmbH	Fuels & Petrochemicals: Ethylene, Benzene
Shell Rhineland Refinery	Cologne (Wesseling/Godorf)	~325 000	Shell Deutschland GmbH	Fuels & Petrochemicals: Ethylene, LPG

Germany has taken a major step toward sustainable chemical production with the launch of its first fully operational facility converting carbon dioxide into ethylene. Located at the Rohrdorfer Cement Plant in Bavaria, this innovative site uses CO_2 electrolysis to transform emissions from cement production into valuable hydrocarbons like ethylene. The project is part of the H2-Reallabor Burghausen initiative, which brings together 37 partners from industry and research to build a circular carbon economy.

The table below outlines key operational details of the facility, including its location, type, purpose, and processing capabilities (Table 14) [17]:

Table 14. Facility converting CO_2 in Ethylene [17].

FACILITY	LOCATION	STORAGE CAPACITY	TYPE	PURPOSE	PROCESSING CAPACITY
Rohrdorfer Cement Plant	Rohrdorf, Bavaria	~30 bar pressurized tanks	CO_2 Electrolysis Plant	Convert CO_2 into ethylene and fuels	Industrial-scale (exact figures not public)

Imports of Oil & Gas

Germany is heavily dependent on imports for fossil fuels:

Oil Imports

- 2023 imports: ~77 million tons of crude oil [18].
- Main suppliers:
  - Norway
  - United States
  - Kazakhstan
- Russia: Once dominant, now phased out due to EU embargo [16].

Natural Gas Imports

- 2023 imports: ~968 TWh of natural gas [15].
- Main suppliers:
  - Norway (43%)
  - Netherlands (26%)
  - Belgium (22%)
- Russia: Pipeline imports ceased in 2022; LNG imports continue in small volumes [16].

Table 15. Comparison of oil and gas domestic production and imports.

CATEGORY	DOMESTIC PRODUCTION (2023)	IMPORTS (2023)	MAIN IMPORT SOURCES
Crude Oil	1.6 million tons	~77 million tons	Norway, USA, Kazakhstan
Natural Gas	4.3 billion m^3	91.75 billion m^3	Norway, Netherlands, Belgium

Germany's energy strategy is shifting toward renewables and LNG infrastructure to reduce reliance on Russian energy and boost energy security.

Import Infrastructure

Germany uses several key terminals to store imported crude oil and natural gas that are later processed into ethylene and other petrochemicals. These terminals serve as critical infrastructure for securing feedstock supply to refineries and chemical plants. Table 16 reports the main terminals used for storing imported ethylene, as well as crude oil or gas aimed to be transformed into Ethylene. Some important remarks are the following:

- Wilhelmshaven and Brunsbüttel LNG terminals are part of Germany's new infrastructure to replace Russian pipeline gas, now feeding into chemical clusters.
- BP Gelsenkirchen and Rehden serve as integrated hubs for both fuel and petrochemical production, including ethylene.
- Advario's terminal (not reported in the table) in Brunsbüttel is being developed specifically for ethylene imports, with potential to handle renewable or circular ethylene sources [19].

Table 16. Import terminals for ethylene, gas and oil (FSRU=Floating Storage Regasification Unit).

TERMINAL NAME	LOCATION	STORAGE CAPACITY	TYPE	PURPOSE	LINKED PROCESSING SITES
Wilhelmshaven LNG Terminal	Wilhelmshaven, Lower Saxony	~5 billion m^3 /year (FSRU capacity)	LNG import & regasification	Feedstock for gas-based ethylene production	Linked to Lower Saxony chemical cluster
Brunsbüttel LNG Terminal	Brunsbüttel, Schleswig-Holstein	~7.5 billion m^3 /year (planned)	LNG import & regasification	Industrial gas supply for petrochemicals	Nearby chemical parks & refineries [20]
BP Gelsenkirchen Storage	Gelsenkirchen, North Rine Westphalia	Integrated refinery tanks	Crude oil & intermediate storage	Ethylene, propylene, and fuel production	BP Gelsenkirchen Complex [21]
Rehden Gas Storage Facility	Rehden, Lower Saxony	~4 billion m^3 (largest in Germany)	Underground gas storage	Buffer for industrial gas supply	Supports regional petrochemical plants [22]

5.1.2.3 Ireland

Oil Production and import

Ireland does not produce crude oil commercially. Hence, all crude oil and ~90% of refined products are imported. The Whitegate Refinery in Cork is Ireland's only refinery, with a capacity of 75 000 barrels/day.

Natural Gas production and import

Ireland's natural gas production declined by 23% in 2023, continuing a downward trend. The Corrib gas field is the main domestic source, operated by Vermilion Energy. The Corrib gas field is located offshore in the Atlantic Ocean, approximately 83 kilometers (52 miles) northwest of County Mayo, Ireland. It lies in the Slyne Trough basin [23].

Imports come primarily via interconnectors from Scotland, with LNG infrastructure under development.

Table 17. Production and imports of crude oil and natural gas in Ireland.

CATEGORY	DOMESTIC PRODUCTION	IMPORTS (2023)	MAIN IMPORT SOURCES
Crude Oil	**None** (no active production)	~64 000 BPD (3.71 million m^3 / year)	North Sea, North Africa, West Africa
Natural Gas	~48 663 TJ (approx. 1.3 bcm)	~138 000 TJ (approx. 3.9 billion m^3 / year)	Scotland (via pipeline), LNG (planned expansion)

Conversion in Ethylene

Based on available data, Ireland does not currently host any dedicated facilities for converting ethylene from crude oil or natural gas. According to the information gathered, most ethylene-based products (like polyethylene) are imported in finished form, bypassing the need for raw ethylene storage.

Imports of PVC resins

Ireland lacks large-scale dedicated PVC resin terminals, several companies handle storage and distribution of PVC materials. These facilities typically store PVC in solid forms (e.g., sheets, rods, granules), not bulk liquid resin, and are geared toward fabrication and distribution rather than raw chemical storage. Unfortunately, PVC resin storage capacities are not publicly listed for Irish distributors or fabricators. [24]

Table 18. Storage of PVC resins, Ireland.

NO	COMPANY LOCATION	FUNCTION	STORAGE TYPE
1	TCL Plastics Ltd	Donabate, Co. Dublin	Distributor of plastic resins incl. PVC
2	Access Plastics Ltd	Ashbourne, Co. Meath	Largest stockist of semi-finished thermoplastics
3	EnviroPlastics Ireland	Co. Clare (near Limerick)	Custom fabrication incl. PVC tanks & piping
4	Abby Plastics	Rathcoole, Co. Dublin	Thermoplastic fabrication incl. PVC vessels
5	TP Polymer Pvt Ltd	Donabate, Dublin	Importer and distributor of PVC compounds and granules
6	Resinex Ireland	Dublin	Polymer distributor with technical support
7	McIvor Industries Ltd	Lifford, Donegal	Manufacturer of PVC and PP packaging products
8	Impact Engineering Plastics	Dublin 24	Multi-plastic stockholder and distributor

Ireland imported over $4.3 billion worth of plastics in 2024, according to UN COMTRADE data [25]. This includes various forms of polymers, with PVC being a significant subset.

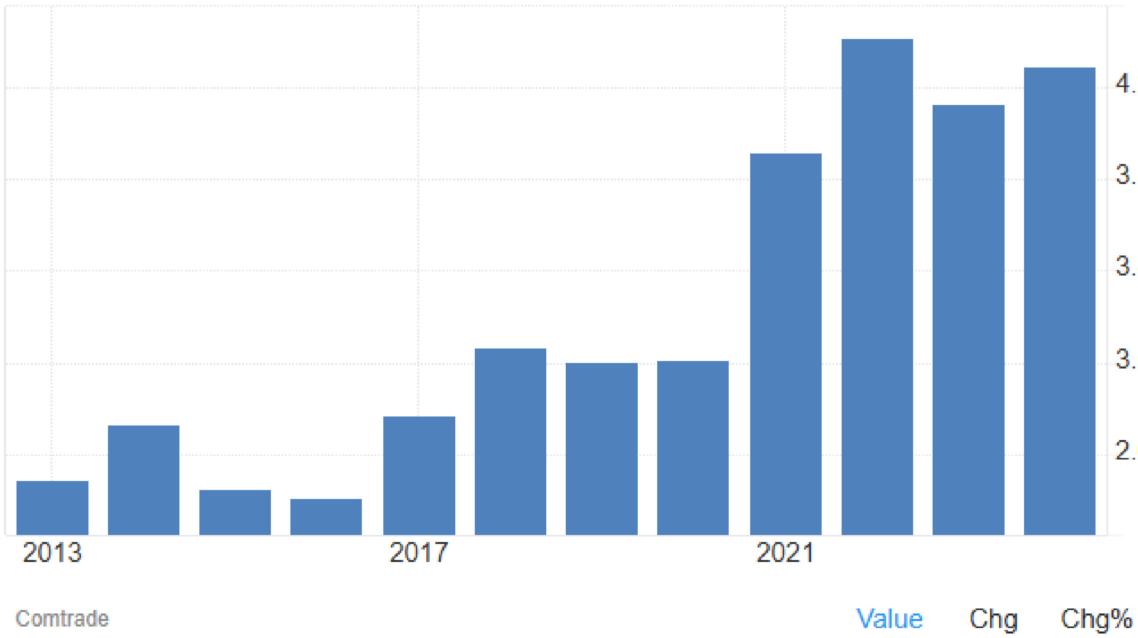

Figure 13. Import data PVC Ireland [25].

5.2 MANIFOLDS

5.2.1 SUPPLY CHAIN

In addition to Uponor pipe plus, a certain number of manifolds will be installed. Manifolds have several roles in Uponor installations:

- **Distribution Hub:** Manifolds act as central hubs that distribute water from the main supply line to various branches throughout the pavement of Riga central market.
- **Improved Flow Control:** the manifolds allow for individual control of each water line. This means that it is possible to control the temperature in selected areas of the pavement. Likewise, a user can shut off water to a single fixture without affecting the rest of the system; this is ideal for maintenance or repairs.
- **Balanced Pressure:** Manifolds help maintain consistent water pressure across all fixtures by reducing the number of fittings and connections, which minimizes pressure drops.
- **Efficient Installation:** Using manifolds with PEX piping simplifies installation. Fewer fittings and joints mean quicker setup and reduced chances of leaks.

Manifolds can be supplied by Uponor's supplier in Europe, located in Germany, Hassfurt.

Manifolds are made primarily of glass fiber-reinforced polyamide (70-80%), brass (about 20%), EPDM (Ethylene Propylene Diene Monomer) (<2%), powder coated steel/plastic (3-5%) and, again, brass and polymer mix (5-7%) (Table 19). Hence, this section will focus on the production and transport of glass fiber-reinforced polyamide.

Table 19. Manifolds' raw materials types and proportion.

COMPONENT	MATERIAL	ESTIMATED PROPORTION BY WEIGHT (%)
Manifold body	Glass fiber-reinforced polyamide	~70-75%
Flow meters	Brass housing, glass inserts	~10-12%
Loop connectors (Eurocone)	Brass (CW614N or CW617N)	~8-10%
Valve components	Brass and polymer mix	~5-7%
Seals and gaskets	EPDM or similar elastomers	~2-3%
Mounting brackets	Powder-coated steel or plastic	~3-5%

** Proportions are estimated for a typical 4-6 loop Vario M manifold*

To manufacture glass fibre-reinforced polyamide (PA-GF), a combination of polyamide resin and glass fibres, along with specific additives and processing conditions are used. A breakdown of the essential materials and components is provided in Table 20.

Table 20. Materials required to manufacture PA-GF.

MATERIAL	FUNCTION	TYPICAL PROPORTION BY WEIGHT (%)
Polyamide Resin (PA6 or PA66)	Matrix material (thermoplastic base)	60-70%
Glass Fibers (E-glass)	Reinforcement for strength and stiffness	30-40%
Coupling Agents (e.g., silanes)	Improve bonding between fibres and resin	0.2-1%
Heat Stabilizers	Protect against thermal degradation	0.5-1%
UV Stabilizers	Prevent degradation from sunlight exposure	0.2-0.5%
Processing Aids (e.g., lubricants)	Enhance flow and moldability	0.1-0.3%
Colorants (optional)	Add colour (black, natural, etc.)	0-2%

The manufacturing process consists of five steps:

- Drying: Polyamide resin must be dried to reduce moisture (typically <0.2%).
- Compounding: Melt the polyamide and mix with glass fibers using a twin-screw extruder.
- Fiber Impregnation: Ensure uniform dispersion and wetting of fibers in the polymer melt.
- Pelletizing: The compounded material is cooled and chopped into pellets.
- Molding/Forming: Pellets are injection molded or compression molded into final parts.

The pellets are shipped to destination, in this case the German facility producing Uponor's manifolds. Upon arrival the materials are stored in the inbound warehouse and thereby adopted to manufacture the necessary components to be shipped to production sites or local warehouses. These are the processes expected:

- **Material Preparation.** Glass fibre-reinforced polyamide (PA-GF) pellets are the base material. Pellets are dried to reduce moisture content.
- **Injection Moulding.** The manifold bars are formed using high-precision injection moulding. This creates the integrated valve seats, loop ports, and mounting features.
- **Flow Meter Integration.** Flow meters (with interchangeable glass inserts) are inserted into moulded slots. These are resistant to dirt and allow visual flow monitoring.
- **Valve Assembly Integrated valves** (supply/return). These may be pre-moulded or assembled separately and snapped or screwed into place.

Quality controls are performed to check for leakage, pressure resistance, and flow accuracy. Flow meters and valve operation are verified. Finally, manifolds are packed with mounting brackets, air vents, and optional accessories. Ready-to-install kits are boxed for distribution.

5.2.2 RAW MATERIALS

Polyamide resins, e.g. PA6, is a high-performance plastic, reinforced with glass fibers to make it stronger and more heat-resistant. This material is derived from caprolactam (from cyclohexane), which is a petroleum product. Being a petroleum based product, the main import and production infrastructure is available in the previous sections of this report.

In Germany, the main manufacturing facilities for glass fiber-reinforced polyamide (PA-GF) are operated by major chemical companies, especially those specializing in engineering plastics. Here are the key players and their sites:

Table 21. Manufacturing facilities of PA-GF, Germany [26], [27].

COMPANY	LOCATION	ESTIMATED ANNUAL PRODUCTION CAPACITY	STORAGE CAPACITY	NOTES
BASF SE	Ludwigshafen	~300 000-400 000 metric tons (PA + PA-GF combined)	Extensive on-site tank farms and silos	Largest Verbund site globally; integrated production of caprolactam, adipic acid, and PA-GF compounds
Lanxess AG	Leverkusen & Krefeld	~100 000-150 000 metric tons (Durethan® PA-GF grades)	Moderate silo and warehouse capacity	Focus on automotive-grade PA-GF; uses backward integration for monomers
Evonik Industries	Marl & Essen	~50 000-80 000 metric tons (PA12 and PA-GF variants)	Specialized storage for high-performance polymers	Produces Vestamid® PA-GF grades; strong in lightweight and specialty applications

COMPANY	LOCATION	ESTIMATED ANNUAL PRODUCTION CAPACITY	STORAGE CAPACITY	NOTES
Ensinger GmbH	Nufringen (near Stuttgart)	~10 000-20 000 metric tons (semi-finished PA-GF products)	Warehouse-based storage	Focus on custom formulations and machining stock (rods, sheets, tubes)
Celanese (Ticona)	Kelsterbach & Frankfurt	~60 000-90 000 metric tons (PA-GF and other engineering plastics)	Integrated logistics hubs	Supplies PA-GF for electrical and industrial sectors

5.3 CABINETS

5.3.1 SUPPLY CHAIN

Cabinets play a vital role in housing and organizing the plumbing system's manifolds and control components. These are adopted for the following purposes:

1. **Protection**: Cabinets shield manifolds, valves, and connections from physical damage, unauthorized access, dust, and moisture, ensuring long-term reliability.
2. **Organization**: They provide a clean, centralized location for multiple pipe connections, making the system easier to manage and maintain.
3. **Accessibility**: Cabinets allow for easy access to shut-off valves and flow meters, which is crucial for maintenance, repairs, or system adjustments.
4. **Aesthetic Integration**: Cabinets help conceal plumbing components, contributing to a neat and professional appearance.
5. **Compliance and Safety**: Proper cabinet installation can help meet building codes and safety standards by ensuring that plumbing components are securely enclosed.

The cabinets that will be installed in Riga, are primarily made of ferrous and non-ferrous ores.

Table 22. Cabinets' raw materials and proportion.

COMPONENT	RAW MATERIALS REQUIRED	PROPORTION OF MATERIALS (%)	PROPORTION OF RAW MATERIALS (%)
Cabinet	• Ferrous ores • Non-ferrous ores	• Steel (Iron + Carbon + Alloys): ~90-95% • Zinc (Galvanization Layer): ~5-10% • A very small percentage of white coat powder (RAL 9016)	• Ferrous ores: ~90-95% • Non-ferrous ores: ~5-10%

Production is performed following three main steps:

1. **Precision Cutting and Forming.** Sheet metal is laser-cut or CNC (Computer Numerical Control) punched to exact dimensions. Bends and folds are formed using press brakes to create the cabinet body and mounting flanges.
2. **Welding and Assembly.** Structural components are spot-welded or mechanically fastened. Internal rails and mounting brackets are added to support manifolds and accessories.
3. **Surface Treatment.** Steel cabinets are powder-coated (typically white) for durability and aesthetics.

5.3.2 RAW MATERIALS

Cabinets are sourced from Uponor's German factory, in Hassfurt. We assume that the same factories producing steel in Germany are the ones that mix with zinc and additional materials and thereby ships the sheets to Hassfurt for firther production. Hence the processes described in section 5.3.1 and related materials sourced are assumed to be the same.

6 RESILIENCE AND SUSTAINABILITY ANALYSIS

6.1 SUPPLY CHAIN FLOW ANALYSIS

In this section, we perform an analysis of the necessary flows of materials, based on the data collected and analysed in section 5. Table 23 shows the number of SKUs, volume and weight expected to be handled by the supply chain aiming to install the solution in Riga.

Table 23. Uponor solution volume and weight.

COMPONENT	M	SKU	VOLUME (M^3)	WEIGHT (KG)
Uponor Pipe Plus	16 000	25	8.8218	1 632
Manifold Vario M	na	16	0.2304	52.8
Cabinets	na	16	1.41816	139.84

Table 24 expounds the quantities of components and raw materials needed for each of the components to be installed in the pavilion.

Table 24. Estimated tier I and tier II supplies for Uponor solution.

COMPONENT	PVC RESIN (KG)	PA-FG (KG)	ETHYLENE (KG)	CRUDE OIL (KG)	ETHANE (KG)	NATURAL GAS (KG)	STEEL
Uponor Pipe Plus	1 387.2	na	693.6	2 621.8	742.15	14 843.04	na
Manifold Vario M	na	34.32	na	48.048	na	na	na
Cabinets	na	na	na	na	na	na	139.84

** Ethylene crude oil route produced assuming naphtha cracking.*

Figure 14 illustrates the main flows and material dependencies in the supply chain for cabinet, pipe, and manifold production.

- **Cabinets** are primarily composed of steel (~90–95%), with zinc (~5-10%) for galvanization and a small amount of white coat powder for finishing. Steel itself is derived from iron, carbon, and alloys.
- **Pipe Plus** is produced from PVC resin, which originates from crude oil and natural gas via intermediates like naphtha, ethane, and ethylene. It is modified with various additives including plasticizers, stabilizers, and fillers.
- **Manifolds** are assembled from PA-GF (polyamide reinforced with glass fibres) and enhanced with coupling agents, stabilizers, and colorants. Components like valves, seals, and connectors complete the assembly.

All final products converge at Riga, indicating a centralized distribution or installation point.
Frome the analysis of the flows, it is possible to notice the following:

- **High Material Intensity.** Steel and PVC dominate the mass flow, indicating high-volume inputs and potential bottlenecks in raw material sourcing, in case of disruptions or scarcity of materials.
- **Complex Additive Networks.** Both pipe and manifold production rely on a wide array of chemical additives, suggesting sensitivity to specialty chemical availability.
- **Multi-source Convergence.** Several final products converge at Riga, implying centralized logistics or installation capacity.
- **Modular Assembly.** The manifold system shows a modular design, with multiple interchangeable components feeding into a single product line. This increases customization possibilities (if needed).

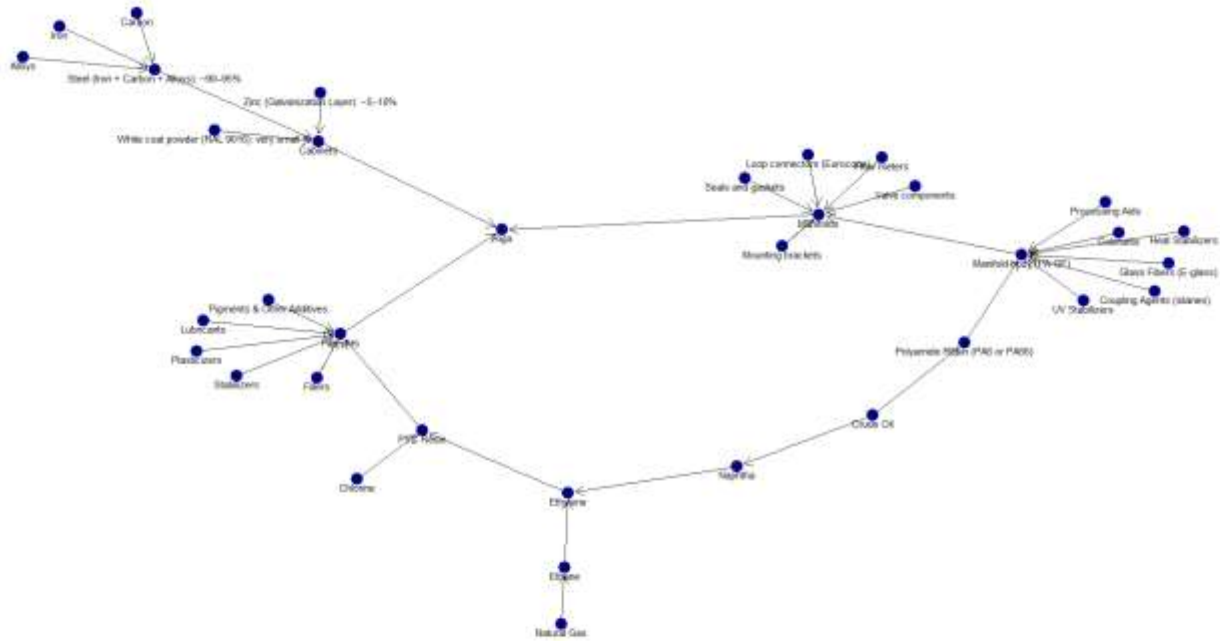

Figure 14. Material and Component Flows for Uponor solution's Supply Chain.

The supply chain flow depicted in Figure 15 illustrates the network of material movement across Germany, Sweden, and Ireland, converging toward the construction site in Riga. From the map we can observe that these three countries are able to ship the Pipe Plus component to Riga site (or nearby storage site). All the three countries serve as a major upstream source, supplying raw materials such as crude oil, ethane, natural gas, and ethylene, which are essential for producing PVC resin and Uponor components. The coloured lines on the map trace the directional flow of these materials, highlighting the interdependence between regions and the logistical coordination required to maintain this transnational supply chain (Figure 15).

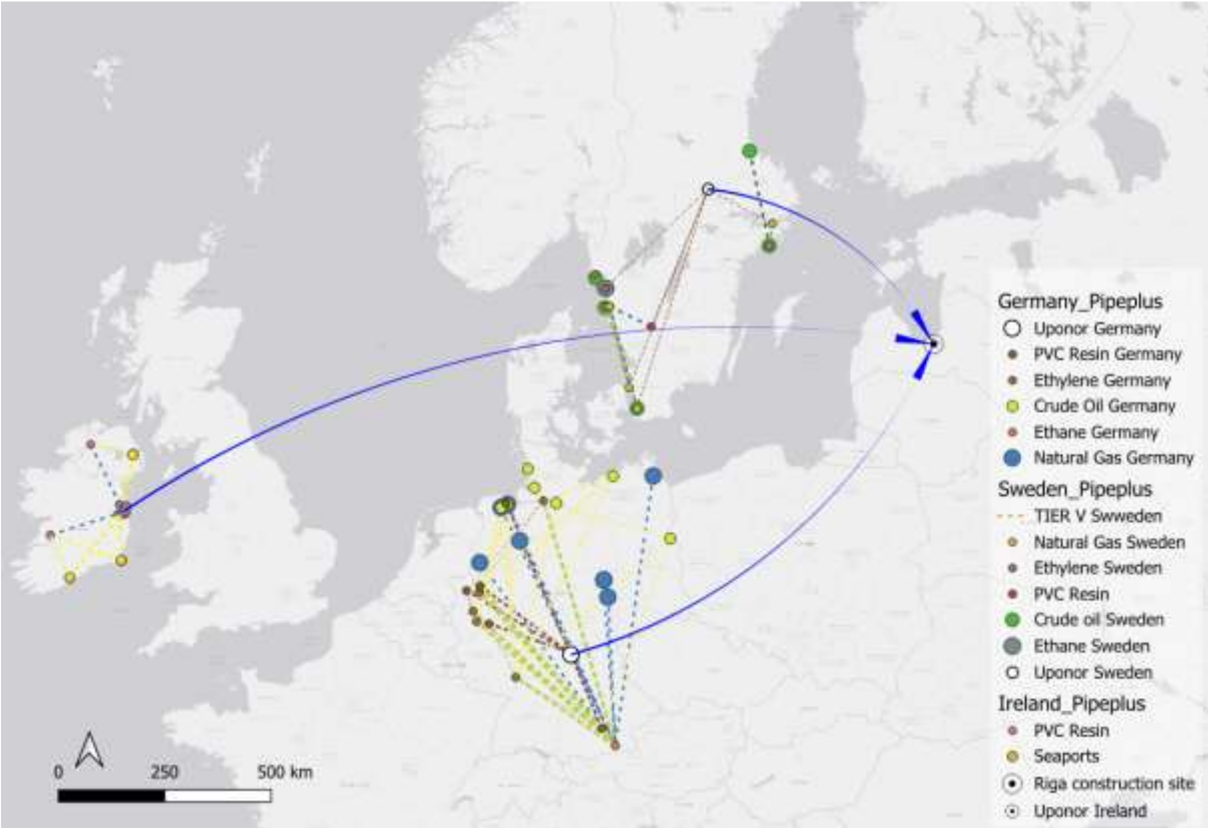

Figure 15. Uponor Pipe Plus supply chain Tiers I to V.

The next two figures, Figure 16 and Figure 17, show respectively the supply chain flows for manifolds and cabinets which are both produced in Germany. Manifolds consist mainly of glass-fibre reinforced polyamide (GF-PA) which can be made available from five factories in Germany (tier II suppliers). Next, these factories are expected to be replenished with PA6 which is a petroleum derived polymer. Therefore, crude oil facilities are expected to replenish the GF-PA factories accordingly (Figure 16). Next, the cabinets are made primarily of steel. Hence, the factory in Hassfurt, is expected to be replenished by four industries located in Germany producing steel sheets (Figure 17).

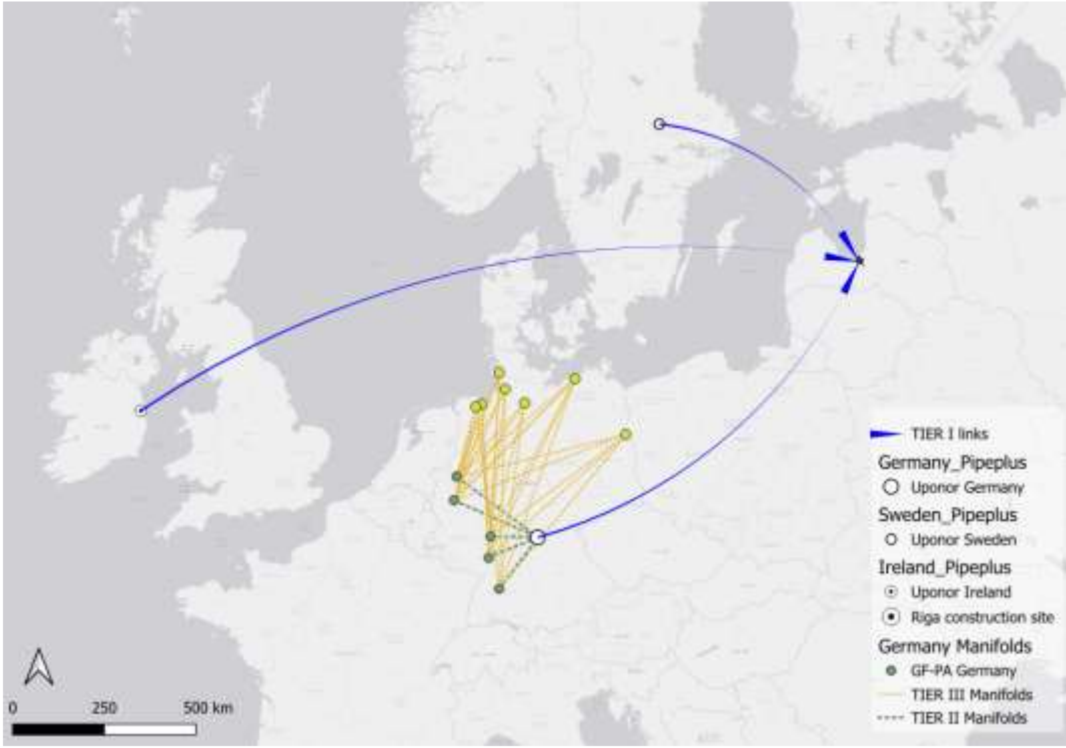

Figure 16. Uponor cabinets supply chain Tiers I to III.

Figure 17. Uponor cabinets supply chain Flow, Tiers I-II.

6.2 WAREHOUSING

Based on the materials to be shipped to Riga, we assume that a total volume of 10.47 m^3 is needed, total weight 1 824.64 kg. To handle the storage of the materials the type of warehousing/storage place is a small to medium sized industrial warehouse. Assuming rack heights of about 2-3 meters (surface occupied about 2 m^2) it is possible to store about 4 m^3 per rack sections, so totally 3 rack sections are needed (6 m^2) (Figure 18). We consider additional aisle space between the racks to allow handling operations, e.g. with forklifts (about 3 x 6 m^2). Hence, totally 24 m^2. In addition, an operational buffer is necessary to allow temporary storage (e.g. staging or inspection) and handling of arriving / leaving cargo in the inbound/outbound areas of the warehouse. Considering the volumes for Uponor's products only, these areas can be approximated to about 25 m^2. The total warehousing area needed is therefore about 50 m^2 (Figure 18).

In addition, the warehouse should be equipped with light duty forklifts, and barcode scanners/RFID for inventory tracking. A Warehouse Management System will be linked to the barcode scanners information to register the incoming, stored and outcoming SKUs and batches.

Finally, basic safety recommendations related to fire protection, ventilation and ergonomics handling are necessary.

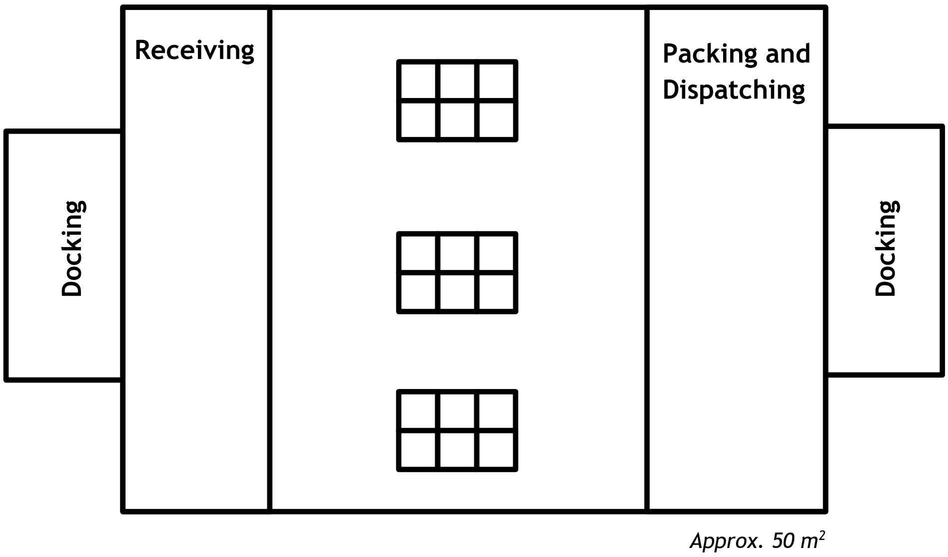

Figure 18. Example warehouse layout for Uponor's materials.

Considering the cold winters, precipitations and possible changes of temperature excursion in Riga (based on the analysis presented in section 4 of this report), it is recommended to evaluate the possibility to use indoor storage in warehouses equipped with basic insulation. Plastics used in manifolds and pipelines to be used in the installation can become brittle at low temperature (<0°C which is possible in Riga during winter, typically dropping below - 10°C). While cabinets made primarily of steel could be subject to corrosion in presence of condensation (possible in Riga due to precipitations and high humidity concerns during winter and spring).

Based on the current storage area available at Uponor site in Riga, an option would be to use container storage, where containers are of type dry or insulated to prevent temperature drop or condensation. Considering the total volume of 10.47 m^3 a single 20ft container would be more than sufficient (capacity of ~33 m^3).

6.3 RESILIENCE ANALYSIS

From a material perspective, we explained before that there are some key chemical additives as well as raw materials that must be available in high volume. Likewise, it is important to monitor and assess their availability to avoid any potential disruption. Those are steel and the connected iron and carbon raw materials, as well as PVC resin and polyamide resin (used for the glass fibre body of the manifolds). These are the major materials to be used for both pipelines and manifolds, in essence plastics. Another important remark from a resilience perspective is that both pipeline and manifolds rely heavily on crude oil. Hence, a disruption in the supply of crude oil would result into a ripple effect on two of the three components analysed in the diagram. Likewise, price volatility of crude oil ultimately increases the double marginalization effects in supply chain, hence, with evident issues in raising costs.

Another relevant highlight from the analysis of resilience is that ethylene could be produced using a secondary route, i.e. natural gas and ethane. This diversification shows that it could be possible to resolve a potential disruption of crude oil, however it remains important to evaluate the consequences of changing the raw material and its effect on the final product, particularly its quality characteristics.

To analyse the resilience of the supply chain network we propose the analysis across three main indicators, betweenness, closeness and eigen vector. Betweenness centrality is a measure of a node's strategic importance in a network, since it quantifies how often a node lies on the shortest paths between other nodes. As reported in Figure 19, it is possible to verifies the importance of some critical elements like the steel, the PVC resin, the ethylene, ethane, naphtha and PA6 or PA66 materials (excluding the components of the solution, manifolds, pipelines and cabinets as these are obviously critical). As these are critical nodes in between the materials and components, it implies that removing these from the network will inevitably disrupt the network.

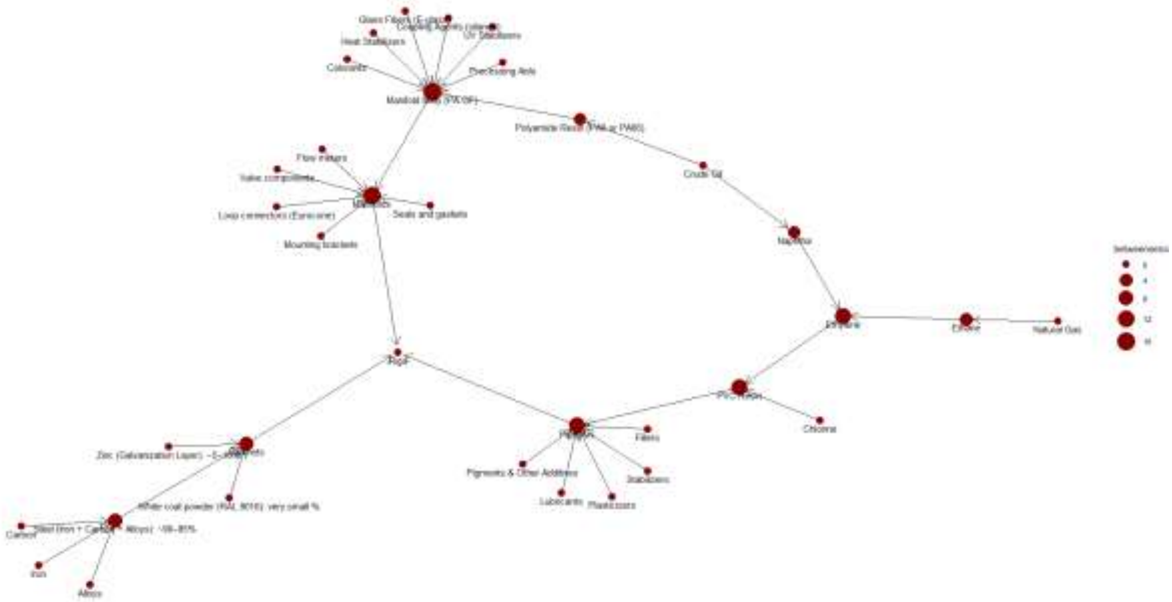

Figure 19. Betweenness centrality map.

Another important measure to understand the criticality of the nodes from a resilience viewpoint is the eigen vector centrality. Eigenvector centrality is a measure of a node's influence in a network, not just based on how many connections it has, but which nodes it's connected to.

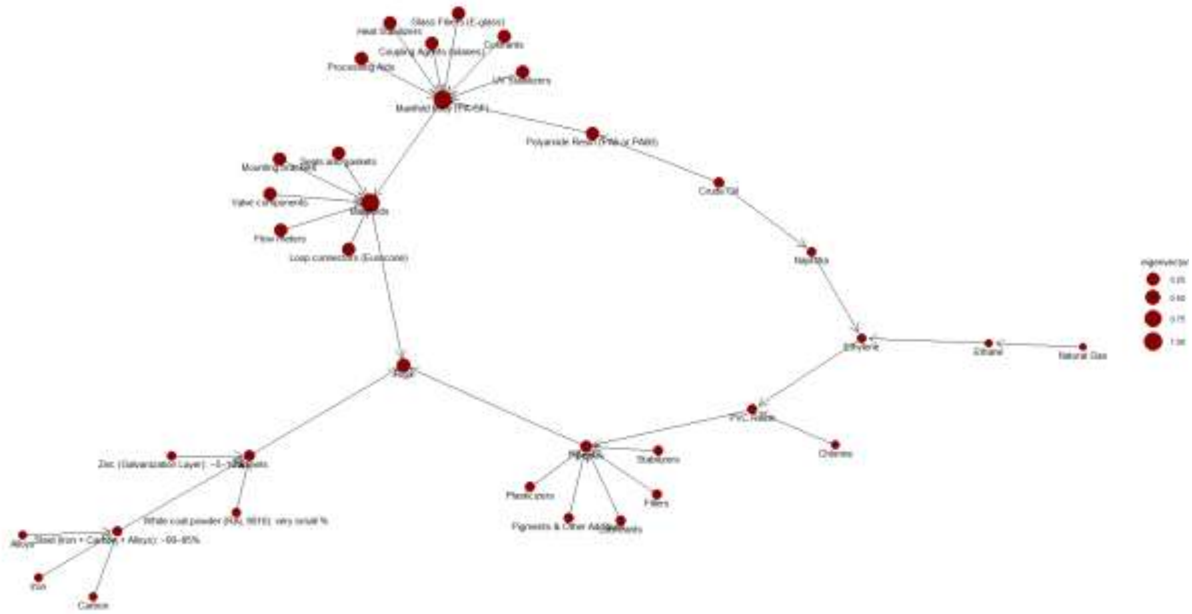

Figure 20. Eigen vector centrality analysis of Uponor supply chain network.

In conclusion, we can put forward the following highlights:

Key Influential Nodes (High Eigenvector Centrality)

These nodes are not just well-connected—they're connected to other influential nodes, making them central to the network's structure:

- **PVC Resin**: Acts as a major hub, receiving inputs from Ethylene and Chlorine and distributing to multiple additives. Its centrality suggests it's a critical intermediate in the production chain.
- **Manifold body (PA-GF)**: Highly connected to various stabilizers, fibers, and agents, indicating its role as a composite product with many dependencies.
- **Steel (Iron + Carbon + Alloys)**: Central in the cabinet production chain, linking foundational materials (Iron, Carbon, Alloys) to surface treatments and coatings.

Bridge Nodes (Likely High Betweenness Centrality)

These nodes likely serve as connectors between distinct parts of the network:

- **Ethylene**: Connects upstream petrochemical sources (Ethane, Naphtha) to downstream products (PVC Resin, Rugal).
- **Manifolds**: Aggregates multiple components and links them to the final destination (Riga), acting as a distribution hub.
- **Polyamide Resin (PA6 or PA66)**: Links crude oil to advanced polymer applications, bridging raw materials and engineered products.

Reachable Nodes (Likely High Closeness Centrality)

Nodes that are well-positioned to reach others quickly:

- **Riga**: is a central node connecting multiple product lines (PVC, Steel, Manifolds), suggesting logistical or organizational importance.
- **Crude Oil**: As a root node, it’s foundational but may have lower closeness due to its distance from end products.

From a resilience perspective, it is possible to identify some critical points. First of all, the suppliers. There are three suppliers of pipelines located in Ireland, Germany and Sweden. The fact that there are multiple suppliers increases the resilience of the supply chain. In this aspect, Uponor could establish specialized contract in order to ensure the possibility to shift production to any of the available suppliers, keeping the supply of materials continuous in case of a disruption.

A clear bottleneck is identified at the supplier in Hassfurt which is responsible for the production of both pipelines, manifolds and cabinets. A disruption of this supplier would inevitably collapse the whole supply chain, making it a key supplier.

6.4 SCALABILITY CONSIDERATIONS

To consider the possibility to scale up the solution, we refer to the analysis performed in section 4 where 1) we show that both weather and climate in Riga are pushing the demand for energy saving heating and cooling solutions and 2) demand growth is simulated and reported in Table 5 and Table 6 expounding the expected growth in 50 years, both annually and in 10 years steps.

In this section, we further simulate how the demand growth for the solution ultimately results into an increased aggregated demand for the supply chain over four decades, from 2035 to 2075. Main results from the simulation are reported in Annex I of this report (Table 28). Material demand scales accordingly, with total weight rising from 172 437 kg in the first period to 178 190 kg by the final decade. PVC resin remains the dominant input, exceeding 10 600 kg throughout, while crude oil and natural gas show the highest volumetric requirements due to their roles in polymer production and energy sourcing. Notably, the volume of natural gas increases from 157 809 m³ to 163 074 m³, underscoring its significance in the supply chain. Reinforced components such as GF-PA and steel maintain consistent growth, supporting structural integrity and system durability. These results provide a clear trajectory for procurement planning, logistics scaling, and sustainability assessments aligned with Riga's long-term infrastructure strategy.

The increased need for materials implies that warehousing or storage space will need to align accordingly. Based on the simulation results for materials needed, we proceed by estimating both warehouse space and number of containers needed to store the components (Table 25).

Table 25. Warehouse capacity estimated as number of containers or, alternatively, storage space (using demand data assuming growth of 1% during 2025-2075).

IOD	COMPONENT	VOLUME (M^3)	WEIGHT (KG)	20FT	WAREHOUSE (M^2)	RACK SPACE (M^2)	STAGING (M^2)	TOTAL
2035-2045	Uponor Pipe Plus	67.53	12 492.86	3	33.765	101.295	40.518	175.578
	Cabinets	10.86	1 070.47	1	5.43	16.29	6.516	28.236
	Manifolds	1.76	404.18	1	0.88	2.64	1.056	4.576
	Total	**80.15**	**13 967.51**	3	40.075	120.225	48.09	208.39
2045-2055	Uponor Pipe Plus	68.28	12 630.82	3	34.14	102.42	40.968	177.528
	Cabinets	10.98	1 082.29	1	5.49	16.47	6.588	28.548
	Manifolds	1.78	408.64	1	0.89	2.67	1.068	4.628
	Total	**81.04**	**14 121.75**	3	40.52	121.56	48.624	210.704
2055-2065	Uponor Pipe Plus	69.02	12 769.36	3	34.51	103.53	41.412	179.452
	Cabinets	11.1	1 094.16	1	5.55	16.65	6.66	28.86
	Manifolds	1.8	413.13	1	0.9	2.7	1.08	4.68
	Total	**81,92**	**14 276.65**	3	40.96	122.88	49.152	212.992
2065-2075	Uponor Pipe Plus	69.78	12 909.69	3	34.89	104.67	41.868	181.428
	Cabinets	11.22	1 106.18	1	5.61	16.83	6.732	29.172
	Manifolds	1.82	417.67	1	0.91	2.73	1.092	4.732
	Total	**82.82**	**14 433.54**	3	41.41	124.23	49.692	215.332

Adopting containers could be the most attractive and less expensive solution. Using containers for storage offers flexibility, mobility, and cost-efficiency, especially for short-term or modular needs.

They can be easily relocated, stacked, and repurposed, making them ideal for dynamic operations or temporary overflow. Containers also require minimal infrastructure and can be deployed quickly. However, they often lack climate control, security, and ergonomic access, which can limit their suitability for sensitive or high-value goods. Operations to load and unload containers require significantly more time affecting safety and damages.

In contrast, a warehouse provides a controlled environment, optimized layout, and integrated logistics capabilities. It supports better inventory management, integration with BIM and Warehouse Management Software, safety standards, and scalability for long-term operations. The downside is higher upfront investment, longer setup time, and reduced mobility.

Among the two options, containers versus warehouse space, if strong demand signals emerge indicating a shared interest in scaling the solution within the city of Riga, we would strongly recommend investing in or renting warehouse space. Warehouses offer a more stable and robust logistics infrastructure, capable of supporting long-term operations, efficient inventory management, and scalable distribution. Unlike containers, which are better suited for temporary or mobile setups, warehouses provide controlled environments, better security, and integration with urban logistics networks. In the context of Riga’s expanding urban development and potential for centralized coordination, a warehouse-based solution ensures resilience, operational continuity, and alignment with future growth.

6.5 SUSTAINABILITY ANALYSIS

In this section the supply chain for delivering products to Riga is assessed in terms of CO_2 emissions. To perform the computations, we assume the following standard estimates:

- **Road freight**: 0.1–0.2 kg CO_2 per ton-km (average: 0.15 kg CO_2/ton-km)
- **Distances** (approximate road distance to Riga):
  - **Dublin** → Riga: ~2 500 km
  - **Virsbo (Sweden)** → Riga: ~600 km
  - **Hassfurt (Germany)** → Riga: ~1 400 km

Table 26 outlines the quantities and specifications of key components to be transported to Riga, including Uponor Pipe Plus, Manifold Vario M, and Cabinets. For each item, the table provides the total length (in meters), number of SKUs, volume (in cubic meters), and weight (in kilograms). Uponor Pipe Plus, which constitutes the largest volume and weight, is shipped from three locations: Dublin, Virsbo, and Hassfurt. In contrast, both Manifolds and Cabinets originate solely from Hassfurt. This data serves as the basis for calculating transport-related CO_2 emissions, factoring in distances, shipment weights, and logistics routes to estimate the environmental impact of inbound deliveries to Riga. The total emissions are 468.2 $KgCO_2$.

Table 26. CO_2 emissions for tier I supply of components to Riga city.

ORIGIN	COMPONENT	WEIGHT (KG)	DISTANCE TO RIGA (KM)	CO_2 FACTOR (KG CO_2/TON-KM)	CO_2 EMISSIONS (KG)
Dublin	Uponor Pipe Plus	544	2 900	0.15	237
Virsbo	Uponor Pipe Plus	544	678	0.15	55.1

Hassfurt	Uponor Pipe Plus	544	1 595	0.15	130
Hassfurt	Manifold Vario M	52.8	1 595	0.15	12.6
Hassfurt	Cabinets	139.84	1 595	0.15	33.5

Finally considering the demand growth which will require to scale up operations in the city of Riga, the new CO2 emissions are reported in the table below. The table presents a decade-by-decade projection of CO_2 emissions associated with transporting Uponor Pipe Plus, Cabinets, and Manifolds to Riga from various European origins. It assumes a steady 1% growth in demand per decade, reflected in increasing shipment weights.

Using a consistent CO_2 emission factor of 0.15 kg CO_2 per ton-km, and average transport distances based on origin (1,700 km for Uponor Pipe Plus, 1 595 km for Cabinets and Manifolds), the emissions are calculated for each component and summed per decade. As oit can be observed in Table 27, emissions increase gradually from 3 539 kg CO_2 in 2035–2045 to 3 658 kg CO_2 in 2065–2075. In addition, the total emissions over 40 years amount to 14 394 kg CO_2, with an average of ~3 599 kg CO_2 per decade. Hence, this reflects the environmental impact of growing demand and highlights the importance of optimizing transport logistics or exploring lower-emission alternatives.

Table 27. Decadal CO_2 emissions forecasts.

PERIOD	COMPONENT	WEIGHT (KG)	DISTANCE (KM)	CO_2 FACTOR	EMISSIONS (KG CO_2)
2035-2045	Uponor Pipe Plus	12 492.86	1 700	0.15	3 186.6
	Cabinets	1 070.47	1 595	0.15	256.0
	Manifolds	404.18	1 595	0.15	96.7
	Total	—	—	—	**3 539.3**
2045-2055	Uponor Pipe Plus	12 630.82	1 700	0.15	3 221.9
	Cabinets	1 082.29	1 595	0.15	258.9
	Manifolds	408.64	1 595	0.15	97.8
	Total	—	—	—	**3 578.6**
2055-2065	Uponor Pipe Plus	12 769.36	1 700	0.15	3 257.5
	Cabinets	1 094.16	1 595	0.15	261.7
	Manifolds	413.13	1 595	0.15	98.9
	Total	—	—	—	**3 618.1**
2065-2075	Uponor Pipe Plus	12 909.69	1 700	0.15	3 294.0

	Cabinets	1 106.18	1 595	0.15	264.4
	Manifolds	417.67	1 595	0.15	100.0
	Total	—	—	—	**3 658.4**

6.6 INTEGRATION IN BIM SYSTEMS

6.6.1 BIM OVERVIEW

Building Information Modeling (BIM) is a digital process that revolutionizes how buildings and infrastructure are designed, constructed, and managed. At its core, BIM involves creating intelligent 3D models that integrate geometric data with functional and informational attributes of every component in a built asset. These models serve as a shared knowledge resource, enabling stakeholders—from architects and engineers to contractors and facility managers—to collaborate more effectively throughout the entire lifecycle of a project.

Unlike traditional 2D drawings or even basic 3D CAD models, BIM systems allow users to simulate real-world performance, detect design conflicts early, and manage construction logistics with precision. For example, a BIM model of a window doesn't just show its shape, it includes data on its manufacturer, material, thermal efficiency, cost, and maintenance schedule. This level of detail supports better decision-making and reduces costly errors.

Modern BIM platforms, such as Autodesk Revit or Trimble Connect, support multi-disciplinary collaboration through cloud-based environments known as Common Data Environments (CDEs). These platforms ensure that all project participants work from a single source of truth, improving transparency and reducing rework.

Beyond design and construction, BIM extends into facility management, renovation planning, and sustainability analysis. It enables building owners to monitor energy usage, schedule maintenance, and plan upgrades using real-time data. As such, BIM is not just a design tool—it's a strategic asset for long-term building performance.

6.6.2 INTEGRATING BIM WITH SUPPLY CHAIN RESILIENCE AND SUSTAINABILITY

The integration of BIM with supply chain analysis, especially in the context of resilience and sustainability, represents a powerful evolution in construction and infrastructure planning. As global supply chains face increasing volatility due to climate change, geopolitical shifts, and resource scarcity, the ability to model and optimize logistics within BIM environments becomes essential.

In our reviewed models, resilience analysis concerns the identification of bottlenecks and potential disruptions in delivering. In this aspect, nowadays BIM models can provide important metrics about necessary materials and dependencies. However, supply chain resilience analysis reported in this document can augment BIM capabilities, simulating and suggesting modular changes in the product, raw materials substitution, route and delivery schedules. The network analysis reported can also visualize dependencies between components and suppliers. Thereby providing planners with enhanced capabilities to anticipate shocks and plan for recovery options. More advanced systems can be used to work with scenario planning and simulation in order to provide more accurate forecasts and emulation of the impacts of possible best practices.

From a sustainability viewpoint, we analyzed the CO_2 emissions associated with transporting construction components (e.g., Uponor Pipe Plus, Cabinets, Manifolds) from various European origins to Riga. By combining BIM's spatial and material data with supply chain metrics, such as transport distances, emission factors, and demand growth projections, we created a dynamic framework for assessing environmental impact over time. These frameworks can be used simultaneously with resilience capabilities and thereby testing supply chain robustness scenarios, while estimating impacts on performance and sustainability metrics. Finally, in our case, we projected emissions over four decades, accounting for a 1% annual growth in demand. This long-term view aligns with BIM's capacity to manage assets across their full lifecycle, from construction to decommissioning.

As an alternative to BIM, our analysis emphasizes the potential usage of Geographic Information Systems (GIS) for supply chain analysis, offering a powerful complementary tool to BIM. GIS enables spatial analysis of infrastructure networks, environmental constraints, and regional logistics hubs, providing geospatial intelligence that can inform site selection, routing optimization, and risk assessment. When layered with BIM data, GIS can help visualize terrain impacts on delivery schedules, identify climate-sensitive zones, and assess proximity to renewable energy sources or low-emission transport corridors. In this aspect, Quantum Geographic Infroamtion System (QGIS) may serve as the visual and spatial interface, allowing users to interact with maps, layers, and geospatial datasets. Custom plugins can be developed using PyQGIS to add domain-specific tools (e.g., resilience modeling, CO_2 tracking).

7 DEVIATIONS TO THE PLAN

The analysis reported in this document is based on a preliminary design (provided early February 2025) of the Uponor solution to be installed in the Riga pavilion. This preliminary design was informally validated as final during the submission of this deliverable. We will now proceed to examine whether the associated Bill of Materials (BoM) corresponds accurately to the finalized design. Any necessary updates to the analysis will be made accordingly and integrated into deliverable D11.4.

8 OUTPUTS FOR OTHER WPS

The work conducted in this Deliverable D8.2 directly supports the objectives of Task 11.4 (D11.4), which aims to test and demonstrate the MULTICLIMACT framework at the Latvian demo site, with a particular focus on the cultural heritage context at both building and urban scales. The supply chain analysis, resilience modeling, and sustainability assessments developed in D8.2 are integral to evaluating the toolkit solutions intended for the Riga demonstrator. Specifically, the methodology for integrating supply chain resilience and sustainability considerations into planning and design activities. The expected objective is to provide robust resilience and sustainability estimation to ultimately improve the resilience of Riga historical center to climate change.

9 CONCLUSION

The primary objective of Deliverable D8.2 was to support the resilience of the built environment by accurately accounting for supply chain dynamics in the context of climate adaptation. The approach centered on applying the design methodology developed in Task 2.2 to a real-world demonstration case in Riga, Latvia. This involved a multi-layered analysis of climate data, material flows, and infrastructure vulnerabilities, combined with detailed mapping of supply chains for key components, Pipe Plus, manifolds, and cabinets. By integrating quantitative forecasting, network theory, and sustainability metrics, the study offers a robust framework for evaluating supply chain performance under evolving environmental and logistical conditions.

Climate forecasts for Riga reveal a clear intensification of summer extremes, with projected increases in both temperature and precipitation throughout 2027 and beyond. Summer rainfall is expected to rise by approximately 17%, while mean summer temperatures could climb by 3.6%, amplifying both stormwater runoff and cooling demand. Autumn warming is even more pronounced, with temperatures forecast to increase by 18% compared to historical averages. These seasonal shifts underscore the need for infrastructure that can withstand concurrent heatwaves and heavy rainfall events. In response to these trends, the demand for energy-efficient heating and cooling solutions is projected to grow steadily. Using a compound annual growth rate of 1% to 4%, the analysis estimates that total building surface coverage in Riga (e.g. considering a 1% compound growth rate, from 211 009 m^2 in 2035 to about 229 447 m^2 by 2075). This translates into rising material requirements and logistical needs, forming the basis for long-term procurement and supply chain planning.

Chapter 5 provides a detailed mapping of the supply chain and raw material dependencies for the three critical components of the Uponor solution: Pipe Plus, manifolds, and cabinets. The Pipe Plus pipelines are sourced from manufacturing facilities in Germany, Sweden, and Ireland, offering geographic diversification and redundancy. Manifolds and cabinets, however, are produced exclusively in Hassfurt, Germany, creating a single-point dependency that poses a resilience risk. Each component's supply chain was mapped across multiple tiers, revealing complex flows of materials and intermediate goods. In terms of raw materials, Pipe Plus production relies heavily on PVC resin, which is derived from ethylene, sourced via crude oil or natural gas. Manifolds are primarily composed of glass fiber-reinforced polyamide (PA-GF), requiring petroleum-based polyamide resins and specialized additives. Cabinets are made from steel, with ferrous and non-ferrous ores as foundational inputs. These dependencies highlight the system’s vulnerability to disruptions in fossil-based supply chains and underscore the importance of monitoring upstream availability and exploring alternative feedstocks.

The volumetric analysis of the Uponor solution reveals a total component volume of approximately 10.47 m^3 and a combined weight of 1 824.64 kg for the initial installation in Riga. Pipe Plus accounts for the largest share, with 16 000 meters of pipeline weighing around 1,632 kg and occupying 8.82 m^3. Manifolds and cabinets contribute smaller volumes, 0.23 m^3 and 1.42 m^3 respectively, but are essential for system integration and control. In terms of raw materials, the solution requires substantial quantities of PVC resin (1 387.2 kg), PA-GF (34.32 kg), and steel (139.84 kg), alongside upstream inputs such as ethylene, crude oil, ethane, and natural gas. These materials are sourced from multi-tier supply chains across Europe, with ethylene production linked to both oil and gas routes. The analysis underscores the material intensity of the system and provides a foundation for scaling logistics, warehousing, and procurement strategies in line with projected demand growth.

A critical aspect of the supply chain strategy involves the local distribution of components within Riga, supported by a dedicated warehouse facility. The initial installation requires approximately 50 m^2 of storage space, sufficient to accommodate the total volume of 10.47 m^3 and weight of 1 824.64

kg. This includes rack space, staging areas, and operational buffers for handling and inspection. Given Riga's cold winters and high humidity, indoor storage with basic insulation is recommended to prevent material degradation, particularly for plastics and steel components. Looking ahead, demand growth projections through 2075 indicate a steady increase in material volumes, necessitating expanded warehousing capacity. By 2065–2075, the estimated requirement rises to over 82 m^3 in volume and 14.4 tons in weight, translating into a total warehouse footprint of approximately 215 m^2. While container-based storage offers short-term flexibility, the report recommends investing in permanent warehouse infrastructure to support long-term scalability, inventory management, and integration with digital planning tools such as BIM and WMS systems.

Based on the analysis of the data gathered, resilience and sustainability were assessed as it follows:

- **Resilience.** The resilience assessment identifies key vulnerabilities and strengths within the Uponor supply chain. While the presence of multiple pipeline suppliers across Ireland, Sweden, and Germany enhances redundancy, the exclusive reliance on the Hassfurt facility for both manifolds and cabinets introduce a critical bottleneck. Network theory metrics, i.e. betweenness and eigenvector centrality, highlight the strategic importance of raw materials such as PVC resin, PA-GF, ethylene, and steel, which serve as bridge nodes and influence hubs within the supply network. The analysis also emphasizes the risk posed by fossil-based dependencies, particularly crude oil, and suggests that ethylene derived from natural gas or ethane could offer a viable alternative. To improve resilience, the report recommends diversifying supplier contracts, exploring bio-based feedstocks, and enhancing modularity in component design to allow for substitution and flexible sourcing.
- **Sustainability.** The sustainability evaluation focuses on the environmental impact of transporting components to Riga. Using a standard emission factor of 0.15 kg CO_2 per ton-km, the report estimates that the initial installation generates approximately 468 kg of CO_2 emissions. Over a 40-year horizon, with a projected 1% annual growth in demand, cumulative emissions are expected to reach 14 394 kg CO_2. Pipe Plus shipments account for the majority of this footprint due to their volume and long transport distances. The analysis underscores the need to optimize logistics routes, consider low-emission transport alternatives, and explore local sourcing where feasible. Integration with BIM systems allows for dynamic tracking of emissions and supports scenario planning for greener supply chain configurations. Overall, the findings advocate for a shift toward more sustainable procurement and distribution strategies aligned with climate adaptation goals.

The integration of supply chain resilience and sustainability analyses into Building Information Modeling (BIM) systems offers a powerful framework for adaptive infrastructure planning. By embedding material dependencies, supplier networks, and transport emissions directly into BIM models, stakeholders can simulate real-world performance, anticipate disruptions, and evaluate environmental impacts throughout the asset lifecycle. Resilience metrics, such as centrality scores and supplier redundancy, can be visualized within BIM environments to support scenario planning and risk mitigation. Similarly, sustainability indicators like CO_2 emissions and material intensity can be tracked and optimized using BIM's spatial and temporal data layers. This convergence enables planners, engineers, and policymakers to make informed decisions that balance operational continuity with climate goals, transforming BIM from a design tool into a strategic platform for resilient and sustainable urban development.

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Annex I

Table 28. Projected Material and Component Requirements (2035-2075): Area, Weight, SKU Count, and Volume by Decade.

Component/Materials	m2 (2035-2045)	Weight (kg)	SKU	Vol (m3)	m2 (2045-2055)	Weight (kg)	SKU	Vol (m3)	m2 (2055-2065)	Weight (kg)	SKU	Vol (m3)	m2 (2065-2075)	Weight (kg)	SKU	Vol (m3)
Uponor Pipe Plus	21 100.00	12 492.86	191	67.53	21 333.00	12 630.82	193	68.28	21 567.00	12 769.36	196	69.02	21 804.00	12 909.69	198	69.78
PVC resin		10 618.93		7.58		10 736.19		7.67		10 853.96		7.75		10 973.23		7.84
Ethylene		5 309.47		4 213.86		5 368.10		4 260.39		5 426.98		4 307.13		5 486.62		4 354.46
Crude Oil		20 069.78		23.61		20 291.41		23.87		20 513.98		24.13		20 739.41		24.40
Ethane		5 681.13		4 177.30		5 743.86		4 223.43		5 806.87		4 269.76		5 870.68		4 316.68
Natural Gas		113 622.58		157 809.14		114 877.28		159 551.77		116 137.35		161 301.88		117 413.59		163 074.43
Manifolds		404.18	122	1.76		408.64	124	1.78		413.13	125	1.80		417.67	127	1.82
GF-PA		262.72		0.20		265.62		0.20		268.53		0.20		271.48		0.20
Crude oil		367.80		0.43		371.87		0.44		375.95		0.44		380.08		0.45
Cabinets		1 070.47	122	10.86		1 082.29	124	10.98		1 094.16	125	11.10		1 106.18	127	11.22
Steel		1 070.47		0.14		1 082.29		0.14		1 094.16		0.14		1 106.18		0.14
Iron		1 466.54		0.19		1 482.73		0.19		1 499.00		0.19		1 515.47		0.19
TOT		**172 436.93**	**436**	**166 312.60**	**21 333.00**	**174 341.09**	**441**	**168 149.13**	**21 567.00**	**176 253.42**	**446**	**169 993.55**	**21 804.00**	**178 190.28**	**451**	**171 861.61**