ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

DEPARTMENT

TITLE

Sustainability in precast company

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Academic Year 2024/2025

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Professor Alessandra Bonoli. Thank you for providing me with this invaluable internship opportunity and for your trust in allowing me freedom to choose my research topic. Your patience, kindness, and guidance throughout this journey have been a constant source of encouragement.

I must also acknowledge Professor Riccardo Fini. It was through your engaging lectures that I first discovered Truzzi S.p.A team. To me, Truzzi was far more than just a workplace; it was a family where empathy, respect and kindness are the cover values. I consider myself incredibly lucky to have had privilege of fulfilling my thesis in such an environment.

I would like to extend my sincere gratitude to Stefano Truzzi. Thank you for giving me the opportunity to be a part of your company and to start my professional journey here. I am deeply grateful that you did not see my initial language barrier—speaking only English at the start—as a limitation. Instead, you trusted me and provided a supportive environment where I could simultaneously gain valuable work experience and master the beautiful Italian language. Thank you for this belief and opportunity.

My thanks go to Giulia, who I first met during my interview. Thank you for believing in my potential and granting me the honor of becoming part of this team, allowing me to learn and grow every day.

I offer my deepest admiration to Roberta. Not only she provided me with crucial technical insights regarding to cement, but also, she taught me a far more valuable lesson: resilience. As a woman standing strong in a male environment, her grace and her power are truly inspiring. She showed me the beauty of maintaining one’s femininity while working with immense strength and professionalism.

A warm thank you to Elena, whose smiling face and kind greetings made every arrival at the company feel welcoming and bright.

A special and profound thanks go to Francesco, who was not only a patient mentor but also a source of immense human kindness. I will never forget your compassion, especially during the terrifying moments of conflict involving Israel and Iran. When I could not reach my family and was consumed by worry, your concern and efforts to comfort me meant more than words can say.

To my family, who are the pillar of my existence:

To my father, who may not have had the opportunity for higher education himself but sacrificed his youth and dedicated his entire life to ensuring I had every opportunity he lacked. Everything I have is a result of your hard work.

To my mother, who has always worried about me more than I worry about myself. Throughout these four years of my study in Italy, despite the physical distance, I have felt

your unwavering support every single day. If I stand here today in this position, it is solely because of the existence and sacrifices of you and father.

To my brother, Pouya. Thank you for being by my side during the darkest days—those days when I would call you in tears, and you were always there to listen. Even if life sometimes pulled us apart, we always found our way back to each other. Through you I learned that family is the most important thing, not only on Earth, but in the entire universe.

To my little sister, Mahla. Although we may not share same blood, you are dearer to me than any blood sister could be. Thank you for being not only a sister but also a kind and compassionate advisor who has always looked out for me.

To my dear friend who is far from me, Anahita. Thank you for being with me through up and downs. Thank you for listening to my pain during those difficult days, even when I knew you were battling your own struggles. You never left me alone, and for that I am eternally grateful.

Finally, I dedicate this work to all of you. This thesis is not merely an academic achievement, but a testament to your love, sacrifice, and enduring belief in me. It is as much yours as it is mine.

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Abstract

The precast concrete industry is traditionally recognized as energy-intensive, facing increasing pressure to mitigate its environmental footprint. This thesis investigates comprehensive decarbonization and circular economy strategies implemented at Truzzi S.p.A., aiming to reduce the Global Warming Potential (GWP) of production without compromising structural integrity or economic viability.

The research focuses on three core areas: the optimization of concrete mix designs, the transition to renewable energy sources, and the implementation of circular waste recovery systems. In the experimental phase, a strength-enhancing admixture (Mapecube1) was introduced to reduce cement content. Results demonstrated that the modified mixes (R50/25 and R5/25) achieved a compressive strength increase of up to 26% at 28 days compared to standard mixes, while reducing specific CO_2 emissions by approximately 21.5 $kgCO_2eq/m^3$.

From an energy perspective, the study analyzes the impact of a 434 kWp photovoltaic system, which successfully covered 38.2% of the facility's electricity demand in 2024. Furthermore, a strategic shift from artificial to natural curing methods resulted in a 93% reduction in methane consumption during winter months, avoiding 116 tons of CO_2eq and generating significant economic savings. Finally, circular economy initiatives, including a zero-liquid discharge water recovery system and the "Multiblock" project for upcycling fresh concrete residue, effectively closed the loop on industrial waste.

This study concludes that integrating high-performance materials with strategic energy management allows precast facilities to decouple production from carbon emissions, proving that industrial sustainability is both technically feasible and economically profitable.

Keywords: *Precast Concrete, Decarbonization, Circular Economy, Low-Carbon Mix Design, Energy Optimization, Sustainable Construction, Carbon footprint, Sustainability, Circular economy.*

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1.Introduction

1.1 Company profile: Truzzi

Truzzi S.p.A. is an industrial prefabrication company established in 1956 by Engineer Luciano Truzzi. Based in Poggio Rusco (Mantua), the company has operated in the construction sector for over sixty years, specializing in the design, production, transportation, and installation of prefabricated structures for industrial, commercial, and logistic purposes. In 2018, the management transition to Stefano Truzzi marked the entry of the third generation, aiming to integrate traditional construction expertise with modern innovation [1].

The production facility spans a total area of 105,576 m^2 and is divided into two primary operational departments, referred to as Plant 1 and Plant 2. While both plants handle core activities such as concrete production, cage assembly, and product storage, specific operations are distributed between them. For instance, metal fabrication is concentrated in Plant 1, whereas the cutting and bending of reinforcement mesh occur in Plant 2. The logistical infrastructure supports the movement of heavy prefabricated elements using overhead cranes and diesel tractors, ensuring efficient handling from casting to final transport **[1].**

A central pillar of the company's current strategy is environmental sustainability. Truzzi S.p.A. prioritizes the implementation of organizational procedures designed to limit environmental impact and promote energy efficiency. This commitment is evidenced by the adoption of renewable energy sources; notably, in 2023, a 430 kWp photovoltaic system was installed on the production facilities, with an estimated annual generation of 500,000 kWh. This transition aligns with the company's broader objective of providing low-carbon technologies and supporting the ecological transition within the construction sector [1].

Figure1. Picture of plant1 and plant2

Figur2. Satellite view of plants

Most of the operational actions in plants 1 and 2 are similar and the activities are stated below:

- Concrete production (in both plants)
- Cutting and bending of rebar and mesh in plant2
- Assembly of reinforcing cages (in both plants)
- Metal fabrication in plant1
- Handling of concrete product with overhead cranes diesel tractors (both plants)
- Storage of product (both plants)
- Framework preparation (both plants)
- Transporting fresh concrete for pouring with diesel concrete mixers (in both plants)
- Transportation of cages and reinforcing bars to production sites with diesel vehicles (in both plants)
- Vibration of framework during pouring, with compressed air vibration (in both plants)
- Artificial curing of products, only in winter: the process is using fined tubes heated by steam produced by 3 thermal power plants for a total of 5 steam generators (in both plants)
- Transport of products to construction sites (in both plants)

Production process in the plants is included below daily activities:

- Removing the production of previous day which has produced
- Movement of manufactured goods
- Cleaning of formwork and application of release oil
- Preparation of armour cage
- Strand tensioning
- Pouring and vibrating fresh concrete

- Natural or artificial maturation

Besides all the above activities, there are also some complementary ones:

- Mesh preparation and reinforcing bars
- Transportation of reinforcing bars
- Assembly of reinforcing bars
- Preparation of inserts and metalwork, workshop department present only in plant1
- Production and transport of concrete
- Handling of products in storage

1.2 Sustainability

Sustainability is defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs [2]. Within the construction sector, building materials significantly influence the environment due to impacts arising from both construction activities and building operations [3]. The concept of sustainability relies on three fundamental pillars: environment, society, and economy. Consequently, sustainable design strategies aim to optimize resource efficiency, reduce project costs, and minimize environmental footprints by utilizing durable materials with extended life cycles, recycling construction waste, and maximizing natural resources such as daylight [3].

1.3 Greenhouse Gases

The greenhouse effect is a natural phenomenon where in the Earth's atmosphere interacts with solar radiation [4]. The sun releases energy in the form of visible light, ultraviolet radiation, and infrared waves. While solar radiation penetrates the atmosphere and is absorbed by the Earth's surface, the re-emitted heat (infrared radiation) is trapped by specific atmospheric gases known as Greenhouse Gases (GHGs), preventing it from escaping into space [5].

The primary GHGs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). When infrared radiation interacts with these molecules, it induces vibrational and rotational movements that re-emit energy, sending heat back into the atmosphere. Rising concentrations of these gases, driven by anthropogenic activities, intensify the greenhouse effect, resulting in global warming, shifts in weather patterns, and rising sea levels [4]. Therefore, addressing climate change requires the adoption of long-term sustainable strategies to reduce GHG emissions [4].

1.4 Emissions from Concrete Production

Global cement production has increased sharply in recent years and now represent third-largest human-generated source of carbon dioxide emissions, following fossil fuel combustion and land-use changes [6]. Cement manufacturing is an energy-intensive process that releases substantial amounts of CO_2, a major greenhouse gas contributing to climate change. Carbon dioxide emissions associated with the cement industry can be categorized into direct and indirect sources [7].

Direct emissions originate from two primary activities in production process. The first involves the chemical conversion of limestone into clinker, a reaction that naturally release

CO_2 as the material's decomposition. The second source of direct emissions comes from the combustion of fuels required to generate the high temperatures needed in the kiln and thermal processes [7].

indirect emissions, in contrast, stem from energy and activities that support production rather than from the chemical and fuel-combustion steps. These include the electricity used operate milling equipment, conveyors, material handling systems, and other machinery throughout the plant [7]. In addition, CO_2 emissions resulting from transportaion considered as indirect emissions which resulting from transportation of raw materials, intermediate products, and finished cement, as they arise from external energy use that enable but does not occur within the main production reactions themselves [7].

Cement is a hydraulic binder composed of finely ground inorganic materials that, when combined with water, form a paste. This paste sets and hardens through a series of exothermic hydration reactions, enabling it to bind particles of solid matter into a cohesive,compact structure [8,9,10]. Once hardend, cement maintains its strength and stabillity, even when exposed to water. When combined with water and fine agggregate such as sand, it forms a composite known as mortar. By contrast, mixing cement with water, sand, and coarse aggregate such as gravel or small stones produces concrete [11]. Cement-based materials, particularly concrete, have been utilized for centuries, primarily in construction and civil engineering applications. Over time, they have become the most extensively used building materials and are now considered the second most consumed resource on planet [12].

Among the various types of cement, Ordinary Portland Cement (OPC) remains the most commonly used [13]. Ordinary Portland Cement (OPC) is a fine grey or white powder composed of calcium silicates, aluminates, and aluminoferrites. The raw materials used to produce these compounds fall into four main categories: calcareous, siliceous, argillaceous, and ferriferous sources. These materials undergo thermal treatment through pyroprocessing and are subsequently subjected to mechanical processing to achieve a product with controlled composiotion and defined mechanical characteristics. The manufacturing of cement generally involves four main stages: quarrying, preparation of the raw mix, clinkering, and final cement production [14].

The production process beings with extraction of raw materials described earlier, which typically consist of a mixture of limestone and clay or shale based components. Limestone serves primarily as source of calcium carbonate ($CaCO_3$), while clays or shale supply silica (SiO_2), alumina (Al_2O_3), and iron oxides such as hematite (Fe_2O_3). These natural rock mixtures from the foundational materials required for cement manufacture [15]. After extraction, the raw materials are initially pre-crushed at the quarry site. The crushed material then undergoes a sereies of blending and sizing opertions designed to achieve the required chemical and physical characteristics of the feed. These preperation steps follow one of two approaches: the dry process or the wet process. In the dry method, limestone and clay are crushed separately and then fed together into a mill for further grinding. In contrast, the wet method involves mixing the clay with water in a wash mill to from a slurry, after which the crushed limestone is incorporated. The resulting finely ground mixture is then dried, subjected to high-temperature treatment in a kiln, and subsequantly cooled. This sequence, known as clinkering, is the core transformative stage in the production of ordinary portland cement. During clinkering, the blended raw materials are converted into clinker-solid grey nodules with a roughly spherical form,typically ranging from about 5 to 25 millimeters in diameter [16].

The chemical transformations that take place within kiln—which heated by the combustion of pulverized coal introduced into the system—are not yet fully understood. The complexity of these reactions is influenced by several factors, including the wide variability in chemical composition of the raw materials, the specific operating conditions of the process, and the practical challenges associated with conducting accurate in-situ sampeling at extremely high temperatures. Despite these limitations, the key chemical reactions and physical changes occuring during this stage can be broadly described as follows:

- Evapration of physically adsorbed water from the raw mixture occurs at relatively low temperatures, typically between 20 and 100 °C.
- Dehydration follows as tempertures rise, leading to breakdown of hydrated minerals and the formation of oxides such as silica, alumina, and hematite.
- Calculation takes between roughly 800 and 1100 °C, during which calcium carbonate decomposes to form calcium oxide according to the reaction:

$CaCO_3 \rightarrow CaO + CO_2$

- At tempertures of about 1100-1300 °C, exothermic reactions lead to the formation of secondary silicate phases, such as:

$2CaO + SiO_2 \rightarrow 2CaO.SiO_2$

- As the material enters the 1300-1450 °C range, sintering and melt-phase reactions occur, converting the secondary silicates into more complex phases, including tricalcium silicate and tetracalcium aluminoferrite:

$2CaO \cdot SiO_2 + CaO \rightarrow 3CaO \cdot SiO_2$
$3CaO \cdot Al_2O_3 + CaO + Fe_2O_3 \rightarrow 4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

- Upon cooling, additional mineral phases crystallize, and the clinker structure is established .

After cooling, clinker is blended with a small proportion of gypsum and ground to produce cement. From an energy perspective, the grinding stage represents the most electricity-intensive operation in typical cement plant. In conventional production lines, electrical energy is used primarily for raw material preparation and for the final grinding of clinker into cement. Once produced, the cement is pneumatically conveyed to storage silos and later dispatched either in paper bags or in bulk containers [17].

1.5Classification of emission in lifecycle assessment (LCA)

To understand the environmental impact of a construction product, it is essential to map its entire life journey from extraction of raw materials to its final disposal. This method is known as Life Cycle Assessment (LCA). According to european standard EN 15804, the lifecycle of building product is divided into specific “Modules” A, B, C, and D [18].

1. The product stage (modules A1-A3)

This is often referred to as "Cradle-to-gate". It covers everything that happens before the product leaves the factory gates. For Truzzi S.p.A. this is the most critical phase as it is directly under the company's control [18].

- A1 (Raw Material Supply): this represents "ingredients" it includes the mining and processing of raw resources (e.g., quarrying limestone for cement, extracting iron ore for steel). The emissionns here come from suppliers.
- A2 (Transport): the logistics of moving these raw materials from the supplier's site to the factory (e.g. diesel consumption of trucks delivering gravel or cement).
- A3 (Manufacturing): the "cooking " process inside the factory. This includes mixing the concrete, the energy used for curing (heating), operating cranes, and internal factory waste.

This thesis mostly focused optimizing Module A3 [18].

2. The construction process stage (Modules A4-A5)

- A4 (Transport to Site): shipping the finished precast products from the factory to the construction site.
- A5 (Installation): the energy and machinery used to lift and fix the panels onto the building structure [21].

3. The Use Stage (Modules B1-B7)

This phase covers the long peiod (often +50 years) during which the building is occupied. It includes maintenance, repair, and the operational energy use (heating/cooling) of the building [21].

4. The End-of-life stage (Modules C1-C4)

This is the "Grave" phase, occuring when the building is demolished.

- C1 (Deconstruction): demolishing the structure.
- C2 (Transport): moving waste to disposal centers
- C3/C4 (Waste Processing/Disposal): Crushing the concrete for recycling or sending it to a landfill [21].

5. Benefits beyond the system (Module D)

- Module D (Reusse, Recovery, Recycling): This is the "Circular Economy" bonus. If the concrete is crushed and reused as road base (instead of using new stone), or if the steel is melted down and recyceld, it creates an environmental "credit" (negative emission) because it prevents the need for new raw materials in future [18].

1.6Concrete production in company (beams and pillars)

the main products in company are coppelle, pillars and multiblocks. This chapter focuses on the comparative analysis of two concrete mixes-one standard and one enhanced with new additive (new mix). The primary objective is to assess and compare their environmental impact, mechanical performance, and cost efficiency. The two concrete mixtures, object of the experimental test, are used for the production of two types of products, such as, the beams (Coppelle) and pillars (Pillastri) [1].

We will analyze the raw materials of the two concrete mixes and the requirements they must meet to produce concrete compliant with the CE-marked products according to the respective harmonized product standards. We will briefly describe the characteristics of the products and the production processes. We will describe in detail the characteristics of the new additive and the experimental tests conducted to demonstrate the product's effectiveness. Following the tests, we will analyze the results and evaluate the benefits in terms of mechanical, environmental, and economic performance [1].

This study also emphasizes the importance of preserving the compressive strength of concrete because although our aim is to reduce the carbon footprint on environment, we want to have same quality of cement or even better than before. Enhancing sustainability must not come at the expense of structural integrity. Thus, maintaining or improving concrete strength while reducing environmental impact is a central aim of this experimental program [1].

Structural elements of interest
We will briefly describe the characteristics of the products produced with the concrete mixes subjected to experimental testing and the related production processes [1].

Coppelle

Coppelle they are straight or curved ribbed slabs produced in reinforced concrete (not prestressed). The cupels feature a double framework of ribs (primary and secondary) arranged orthogonally to each other and along the two primary directions. The secondary ribs define a square area, 18 cm on each side, enclosed by a thin concrete slab one centimeter thick. This slab acts as a closure, similar to a skylight, separating the building's exterior and interior. Therefore, it is considered (structurally) as a mass applied to the load-bearing structure [1].

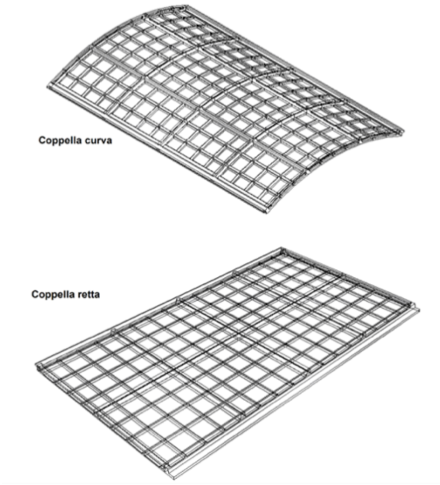
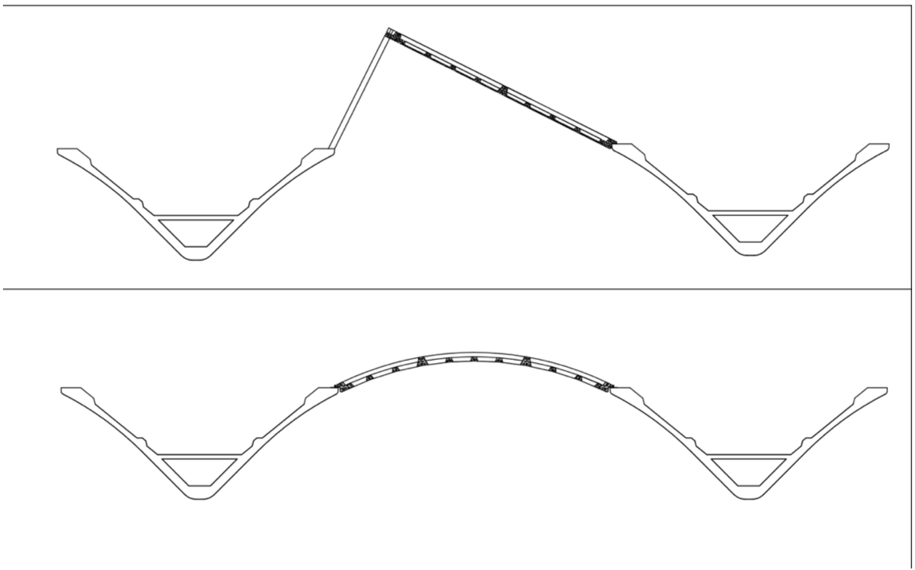


Figure3. picture of the types of roof shape

The shed and curved roofing elements are complementary roofing elements and are CE marked according to the harmonized standard EN 13693. These define the roofing of a shed between the roofing tiles (Ondal, Superondal, and Contrast). An image showing the final assembly configuration of the roofing elements before the insulation and waterproofing phase is provided [1].



Fifure4. final assembly configuration of the roofing elements

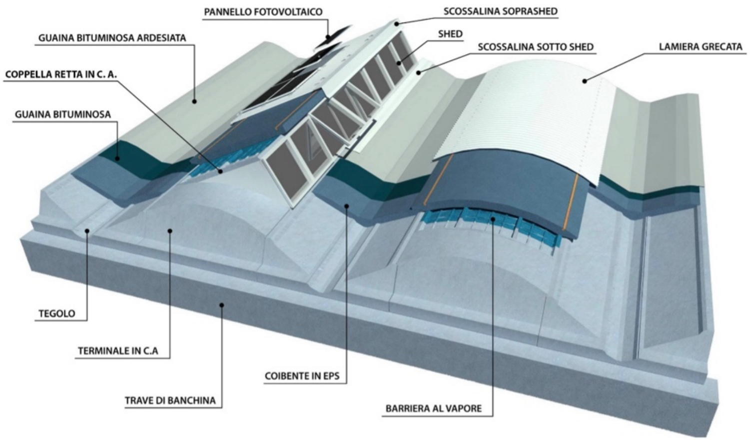


Figure 5. Detailed stratigraphy of the roofing system with photovoltaic integration

Coppelle are produced with concrete mix called R40/13 with a characteristic compressive strength of 50 MPa and reinforced with mesh and reinforcing bars of the B450A/C type with improved bond. Given the modest thicknesses of the cupels, the concrete mix is very rich in fine fraction, composed mainly of sand and cement and produced with a very fluid consistency. We will analyze the concrete mix design in detail in the section on the experimental tests [1].

The cupels are produced in multi-pocket moulds, in each of which only one cupel of 4 metres width can be produced and, in some special pockets, from 1 to 4 cupels of width multiples of 1 meter (4 of 1 meter, 2 of 2 meters, 1 of 1 meter + 1 of 3 meters) [1].

Pillars

Pillars are primary structural elements that transfer vertical and horizontal forces to the foundations. They are CE-marked construction products in accordance with the harmonized standard EN 13225. They can have cross-sections ranging from 40x40 cm to 100x130 cm and lengths of up to 20 meters. They are manufactured using modular formwork that allows for the construction of a considerable number of brackets along the length of the column [1].

Figure 6. Casting process of precast pillar elements

In addition to being able to withstand stress, pillars must also be able to transmit forces from the floors and/or roof to the foundations. To ensure this, they must be securely anchored to the foundations. There are various types of foundations and various fastening techniques that ensure a solid and reliable connection [1].

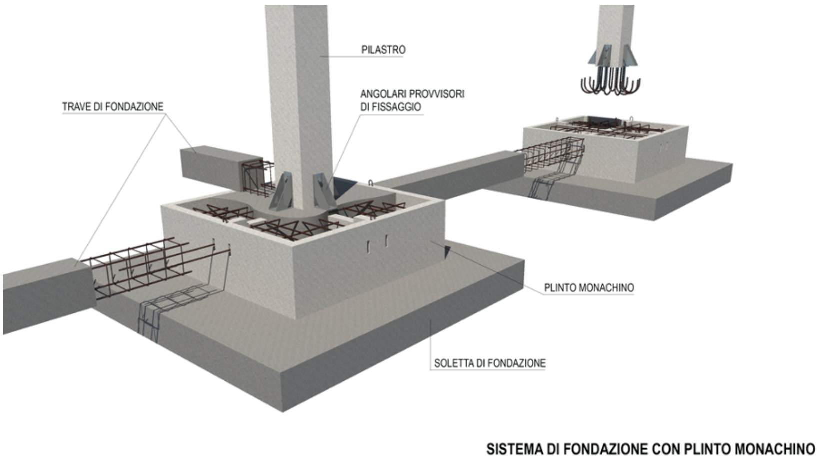


Figure 7. Foundation system details using the Monachino plinth connection

The pillars are made with a concrete mix called R4/19 with a characteristic compressive strength of 50 MPa and B450A/C steel reinforcement [1].
Unlike the above-mentioned mix R40/13 mix used for the cupels, the concrete used for the pillars is very consistent with a workability class of S4. During casting the concrete is subjected to a significant vibration transmitted by the formwork, thanks to compressed air vibrators, which guarantees excellent compaction and therefore durability of the concrete [1].
Production Processes
Both the cupels and pillars follow a daily production cycle consisting of the following phases:
- Removal of the pieces produced the previous day
- Cleaning the formwork
- Oiling the formwork with release agent

- Preparation of the reinforcing cages
- Insertion of the reinforcing cages into the formwork
- Application of spacers to ensure proper concrete cover
- Verification by internal inspectors of the correct size and position of the reinforcing bars and spacers.
- Pouring of concrete into the formwork, resulting in vibration of the concrete.
- Curing of the concrete

The concrete is poured using a Speedy concrete pouring vehicle. This vehicle consists of a support with rubber wheels, a hopper with a capacity of approximately 4 cubic meters, a mechanical arm containing a longitudinal auger approximately 7 meters long for concrete evacuation, and a cockpit and control unit. It is also equipped with a 360° rotation and tilt system for the hopper, auger, and driver's cabin, allowing it to reach all the necessary concrete pouring positions, depending on the formwork [1].

Figure 8. speedy machin for puoring concret

1.7Raw material

This section describes the main characteristics of the raw materials used to produce concrete. The basic components are the same for both the R40/13 mix design (used for the cupels) and the R4/19 mix (used for the pillars); what varies are the dosages, which directly influence the final properties of the concrete, particularly its consistency and mechanical strength [1].

Natural Aggregates

Natural aggregates used in concrete production are inert materials obtained by mechanically crushing natural rocks, selected based on their physical and mechanical properties. Unlike simply washed or sifted natural aggregates, these undergo a crushing process that gives them a more angular shape and a rougher surface [1].
These characteristics improve adhesion to the cement paste, increasing the mechanical strength and durability of the concrete. Crushed aggregates must meet specific regulatory requirements in terms of grain size, impurity content, resistance to fragmentation, and water absorption. The aggregates used by Truzzi S.p.A. are sand 0/6 and medium crushed stone 6/14, and are CE marked according to the harmonized standard EN 12620 [1].

Industrial aggregate

Industrial aggregate is a recycled mineral aggregate obtained from industrial byproducts. Specifically, it is carbon steel slag from an electric arc furnace (EAF-C). After appropriate treatment, which includes cooling, crushing, and magnetic separation, it is used as a high-performance aggregate. It is CE certified according to the harmonized standard EN 12620 and complies with the technical requirements for concrete production. The use of this industrial aggregate helps reduce the extraction of virgin raw materials and avoids landfilling of industrial waste. Its reuse supports the principle of the circular economy and significantly reduces the environmental impact of concrete [1].

Cement

The cement used in the mixes examined is characterized by a reduced clinker content, supplemented with fly ash and limestone. This reduces the carbon content of the mix while maintaining its strength and durability. Specifically, the cement used is a CEM II B (reduced clinker content from 65 to 79%) blend containing two additives; its full code is CEM II/BM (P-LL) 42.5 R. The cement is produced elsewhere and must be delivered via a combination of sea and road transport, optimized to minimize CO2 emissions [1].
The cement, CE marked according to the harmonized standard EN 197-1, complies with the technical requirements for concrete production [1].

Superplasticizer

Concrete admixtures are chemicals added in small quantities (usually <5% of the cement weight) to the concrete mix to modify certain properties, both in the fresh and hardened state [1].
Main types of admixtures:

- Water reducers (plasticizers and superplasticizers)
- Set retarders
- Setting or hardening accelerators
- Antifreeze
- Waterproofing agents
- Corrosion inhibitors
- Air entrainers

The admixtures used to produce the mixes in question are superplasticizers [1].
Superplasticizers (also called highly effective water reducers) are additives that significantly improve the workability of fresh concrete without increasing the water/cement ratio. They can also be used to drastically reduce the water content in the mix, increasing mechanical strength while maintaining the same workability [1].

Main functions

- Increase concrete fluidity (self-leveling and pumpable)
- Allow significant water reduction (up to 30%)
- Improve mechanical strength (thanks to the lower w/c ratio)
- Allow better compaction (reduced porosity)
- Optimize casting in complex or heavily reinforced formwork

The additives used are CE marked according to the EN 934-2 standard and comply with the technical requirements for concrete production [1]

1.8 Utilization of green energy in production and optimization of processes for emission minimization

the purpose of this section is to analyze the energy consumption at two plants and to discuss and determine the ways for saving energy and the impact on CO_2 eq emissions due to the use of photovoltaic system and a new strategy for reducing methane consumption [1].

The reference year for the energy analysis is 2024, when the photovoltaic systems were in continuous operation throughout the entire year. Since there is no energy storage (battery), the electrical energy produced by the PV installation is either self-consumed or fed into the national grid, meaning that energy consumption coincides with real-time production and demand profile of the plant [1].

The plants identified here (in plant1 and 2 which we introduced earlier) that use electricity are concrete batching plants, compressors and dryers, overhead cranes, lighting fixtures, auxiliary processes (hydraulic power units), purification (Beton wash) and curing (steam generator). Each plant is equipped with a photovoltaic system with total power output of 434 kWp for electricity production [1].

The main source of providing energy is divided in 3 groups: natural gas, diesel, and electricity. The specifies of these three sources and their intended uses will be discussed later [1].

- natural gas (methane):

The use of methane gas, as a fossil fuel, leads to direct CO_2 emissions at the plant. However, methane produces fewer pollutants than diesel or heavy fuel oil, making it a cleaner fuel [19]. Natural gas is mainly used for the Artificial Curing of Concrete process, especially during the colder months, thanks to three thermal power plants located throughout the plants [1].

- diesel:

Diesel fuel is the most polluting energy source in the factory, and its consumption causes direct emissions of CO_2 and particulate matter (PM) [20]. The company is evaluating the gradual replacement of diesel machinery with electric or hybrid models to reduce these impacts. Diesel fuel is used for the transportation of concrete, semi-finished products, and finished products [1].

- electricity:

Electricity is supplied by National electricity grid and a 434 kWp photovoltaic system installed on the factory roofs [1]. Purchased electricity may cause indirect CO_2 emissions since they are partly produced from fossil fuels [21]. Electricity is main source of energy for production lines, lighting, compressors, and industrial equipment [1].

Factory uses electricity, natural gas and diesel fuel; the consumption of each energy source is measured with its own unit of measurement in the International System [1].
These units of measurement are:

- Electrical energy: kWh, a measure of the amount of work or energy consumed over time, a kilowatt-hour is the amount of energy consumed by a device with a power of 1 kilowatt operating in 1 hour [22].
- Natural gas: Scm (standard cubic meter), measure the quantity of gas contained in a cubic meter at standard temperature (15 c°) and pressure (1,013 millibar, standard atmospheric pressure) conditions [23].
- Diesel: liters. To compare energy consumption across fuels, we must convert all energy consumption units into a single equivalent unit TEP. TEP is an international standard unit of measurement for energy, used to compare energy production from

different sources. A ton of oil equivalent is amount of energy obtained from burning one tone of average crude oil of a specific quality [24].

To better understand the role of TEP, the approximate relationship for converting different units into TEP is as follows [1]:

Type of energy	Conversion factors from DECREE
Electricity (kWh)	0,00023 TEP/kWh
Natural gas (Smc)	0,00082 TEP/Smc
Diesel (liter)	0,000902 TEP/liter

Table. 1 Conversion factors of energy sources to Ton of Oil Equivalent (TEP)

The table below shows the conversion factors provided for an Italian legislative decree:

- Electricity: the conversion factor for electricity supplied at high and medium voltage is 0,23 TEP/MWh ➔ 0,00023 TEP/kWh

- Natural gas: 0,82 TEP/1000Nm^3 (Nm^3 = Smc) ➔0,00082 TEP/Scm

- Diesel: 1,08 TEP/ton x 0,000835 ton/liter = 0,0009018

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ALLEGATO *A*

ALLEGATO N. 3

TABELLA DI CONVERSIONE TEP

		TEP
Combustibili liquidi *(Valori in tonnellate equivalenti)*	Gasolio	1,08
	Olio combustibile	0,98
	Gas di petrolio liquefatti (GPL)	1,1
	Benzine	1,2
Combustibili solidi *(Valori in tonnellate equivalenti)*	Carbon fossile	0,74
	Carbone di legna	0,75
	Antracite e prodotti antracinosi	0,7
	Legna da ardere	0,45
	Lignite	0,25
Combustibili gassosi *(Valori in 1000 Nm^3 equivalenti)*	Gas naturale	0,82
Elettricità *(Valori in MWh equivalenti)*	Fornita in alta e media tensione	0,23
	Fornita in bassa tensione	0,25

— 85 —

Figure 9. Official TEP conversion table from the Italian Legislative Decree

At Truzzi plant, energy is supplied through two main networks: the national electricity grid and national natural gas grid. Each of these two sources is connected to the plant through dedicated points [1].

Electricity is supplied by the medium voltage grid (MV) and a separate delivery point is defined for each of the two production sites (plant1 and plant2). These points, known by POD codes, are where electricity enters the plant from the grid and is measured and invoiced by the energy supplier. Each site has a specific contractual power capacity, and actual consumption is monitored through data recorded on these meters. Electricity is used in all production areas, including the concrete batching plants, overhead cranes, compressors, lighting and auxiliary equipment [1].

Natural gas also enters the plant from the municipal gas network through 3 separate delivery points, known as PDRs, which supply gas to power the thermal units (thermal power plants). The plant is equipped with a total of three thermal units and five boilers. Natural gas is burned in these boilers to provide hot water for the concrete production and steam for the concrete's artificial curing process during the winter. These delivery points are equipped with Scm consumption recording devices [1].

In addition to two these fossil fuel sources, the factory is also equipped with photovoltaic systems. A solar array has been installed at both production sites. These systems were fully operational in the base year 2024. Since there is no battery storage system at the facility, solar energy is consumed instantly, and whenever production exceeds consumption, the surplus is fed into the grid [1].

The concept of solar panel (photovoltaic) involves directly capturing light of the sun and converting it into electricity. This process is based on physical phenomenon called photovoltaic effect [25].
A simple operation process:
1-capturing light: each solar panel is made of small semiconductor cells (usually silicon). When sunlight (photons) strikes the surface of these cells, the photons' energy is transferred to electrons within the material [25].
2- current generation: this energy causes electrons to separate from their atoms and move in a specific direction. This regular movement of electrons is known as direct current (DC) electricity [26].
3-conversion to AC: since most industrial equipment (such as motors and machinery) operates on altering current (AC), the DC power generated is passed through a device called an inverter. The inverter converts the DC current into standard AC current that can be fed into the facility's internal grid [26].
4-internal consumption: this alternating current is used directly to power the operating needs of the plant (compressors, lightning, machinery). Installation location on the company premises [1].

According to standards and given the nature of a large production site like Truzzi S.p.A. photovoltaic systems are typically installed in the location with the most available space and the greatest exposure to direct sunlight: in industrial factories, the largest available surface is roof of sheds and production halls [1].

To compare energy performance across years and assess overall efficiency, all data was measured in standard units: kilowatt hours (kWh) for electricity and standard cubic meters (Smc) for natural gas. These were then converted to the reference unit TEP (ton of oil equivalent). Furthermore, to normalize the results and measure productivity, energy consumption is calculated based on the quantity of concrete produced, allowing for the ratio between energy consumed and cubic meter of concrete produced [1].

Energy and natural gas can therefore be determined. We will talk about real energy consumption in factory, and greenhouse gas reduction. A great portion of energy consumption in world is generated by combustion of fuels such as gas, oil, coal which result in greenhouse gas emissions [1].

At the Truzzi company, after pouring and vibrating fresh concrete, two methods are used to accelerate the curing process:
-natural maturation
-artificial maturation
Artificial curing is only done in winter, because concrete hardens naturally at low temperature. For this purpose, the company uses a thermal steam system:
The artificial curing of products, only in the winter, through finned tubes heated by the steam produced by 3 thermal power plants for total of 5 steam generators (in both plants) [1].

How the thermal process works:
1.Natural gas is used as the primary fuel for the boilers
2.The boilers produce steam at the appropriate pressure.
3.The steam is conveyed to the curing rooms via an internal piping network.
4.The finned tubes inside the curing tunnels maintain a uniform and high ambient temperature.
5.The heat evaporates surface water and accelerates the chemical hydration reaction of the cement [1].
This process allows concrete products to reach the required mechanical strength more quickly and allows the factory to continue production even in winter [1].
This process allows concrete products to reach the required mechanical strength more quickly and allows the plant to continue production even in winter [1].

It is then possible to determine the energy and natural gas consumption. We will discuss the actual energy consumption in the factory and the reduction of greenhouse gases.

1.9Circular economy

Truzzi S.p.A. has expanded its sustainability strategy beyond energy efficiency to embrace the full principles of Circular Economy. The goal is to transition from a linear “take-make-dispose” model to a regenerative system where material kept in use and waste is designed out of process [1].

What is circular economy? Traditionally, industries operate on a “Linear Economy” model, often described as take, make and dispose. In this outdated system, raw materials are extracted from nature, processed into products, and eventually discarded as waste at the end of their life [27].

On the other hand, the Circular Economy is a regenerative model designed to decouple economic growth from the consumption of finite resources [28].

It follows the goal to close the loop, ensuring that products, components, and materials are kept in use for as long as possible. In circular system, waste does not exist anymore but, we generate by-product and each by-product viewed as a valuable resource to be fed back into the production cycle [29].

The implementation of the circular economy strategy at company is driven 3 fundamental objectives designed to minimize environmental impact while optimizing operational efficiency:

1. Zero waste generation (process water): to eliminate the production of filtration sludge and reduce electricity consumption by decommissioning the traditional filter press system in favor of direct water recovery.
2. Material valorization (Fresh concrete): to achieve “zero material waste” by transforming residual fresh concrete into marketable construction elements named Multiblock, in this way converting a potential disposal cost into a revenue stream.
3. Resource preservation (supply chain): to reduce the depletion of virgin natural resources (sand and gravel) by integrating certified “end-of-waste” recycled aggregate DIMA into the production cycle, lowering the embodied carbon of the final product [1].

2. Problem description

The precast concrete industry is traditionally recognized as a resource-intensive sector with a significant environmental footprint. This thesis identifies three critical challenges inherent in the standard production process that necessitate urgent intervention:

2.1 CO_2 emission due to concrete production

Traditional mix designs rely heavily on Portland cement, the production of which is responsible for massive portion of global CO_2 emissions (due to the calcination of clinker and high kiln temperatures). The standard practice of using high factors to guarantee early strength results in products with a very high "Embodied Carbon" footprint, making the material itself the largest source of emission in the sector [30].

2.2 Fossil fuel dependency and energy composition

Standard prefabrication processes are energy-intensive, particularly during the curing phase. Historically, the industry relies on natural gas (methane) to heat production beds and accelerate concrete hardening, especially during winter month (scope 1 emissions). Furthermore, the heavy machinery and plant operations depend on grid electricity, which often comes from non-renewable sources (scope 2 emissions) [31]. This dependency not only generate greenhouse gases but also exposes the company to volatile energy market costs.

2.3Linear waste generation

The traditional production model follows a linear approach which is take-make-dispose, in this way generates significant waste stream. Two remarkable issues are:

- Process water: the daily washing of mixers and trucks generates large volumes of water contaminated with cement and fines. Traditionally, this requires complex filtration (filter press), consuming energy and producing "sludge" waste that must be landfilled.
- Fresh concrete residue: the other problem is unavoidable surplus concrete left in mixers or returned in trucks is typically treated as waste material, requiring crushing and disposal. Additionally, the continuous extraction of virgin natural aggregates (sand and gravel) depletes finite natural resources, further straining the environmental impact of the supply chain [32].

3. Concrete taste and data analysis

Experimental Program

3.1 Objective

The study's objective is to formulate a concrete mix with a lower environmental impact by reducing the cement dosage without compromising mechanical properties. Of all the raw materials listed above, cement is the material with the greatest environmental impact in the mix. The table below shows the environmental impacts resulting from the production alone (GWP phases A1-A3) of the individual raw materials that make up the concrete mix [1].

Raw material	GWP (phases A1-A3)	Unit of measure
Cement - CEM II/BM (P-LL) 42.5 R	613	kg CO2eq./ton
Natural aggregates	2,97	kg CO2eq./ton
Industrial aggregates	4,08	kg CO2eq./ton
Superplastificizer additive	1530	kg CO2eq./ton

Table 2. Global Warming Potential of individual concrete components

To achieve this goal, we will introduce an additional raw material into the concrete mix design. In recent years, the concrete chemicals industry has developed strength-enhancing admixtures. Specifically, the admixture used is Mapecube1, produced by Mapei S.p.A., an Italian multinational leader in the production of chemical products for the construction industry. Mapecube1 optimizes the performance of cements, even those with low clinker content, by optimizing clinker hydration and achieving maximum concrete performance. Its purposes may include:

- Increase the strength of existing concrete.
- Maintain the current strength of the concrete while reducing the cement content.

This second objective is the goal the company intends to achieve.

3.2 Mix analysis

This section details the mix design composition and evaluates the indirect environmental impacts—specifically those associated with raw material production—for both the baseline and the optimized concrete formulations [1].

3.2.1 Copelle

R40

Raw material	Quantity [Kg-Liters]	Humidity	Chlorides	Weight	Recycled	Volume mix	GWP production
CEM II B-M (P-LL) 42,5 N FINTITAN	640 kg		256 grams	640 kg	36 Kg	203,17 liters	392,32 kg CO_2eq/m^3
Sand 0-6	990 kg	6,00%	10 grams	990 kg	0 kg	373,58 liters	2,94 kg CO_2eq/m^3
Industrial aggregate 4-8	310 kg	1,00%	31 grams	310 kg	310 kg	83,11 liters	1,26 kg CO_2eq/m^3
Medium Gravel 6-14	165 kg	1,00%	2 grams	165 kg	0 kg	62,26 liters	0,49 kg CO_2eq/m^3
Superplastificizer additive	3,40 liters		0 grams	4 kg	0 kg	3,21 liters	5,51 kg CO_2eq/m^3
Aqueduct	256,00 liters		28 grams	256 kg		256,00 liters	
A/C max	0,40						
Total water	256,00 liters	Chloride content	326 grams	2365 kg/m^3	346 kg/m^3	1001,34 liters	402,53 kg CO_2eq/m^3
		chloride limit value	1280 grams				
Air incorporated	20 liters	Check chloride content	Verify	% by weight of recycled		14,65%	

Table 3. Detailed mix design composition and GWP analysis for R40/13 (Standard Mix)

The analysis of Table 3 confirms that any strategy to significantly decarbonize this concrete must focus on **reducing the cement dosage**, as it is the single overwhelming driver of the mix's carbon footprint.

R50/25 (new mix)

Raw material	Quantity [kg-Liters]	Humidity	chlorides	weight	recycled	Volume and mix	GWP production
CEM II B-M (P-LL) 42,5 N FINTITAN	600 kg		240 grams	600 kg	34 kg	190,48 liters	367,80 kg CO_2eq/m^3
Sand 0-6	1050 kg	6,00%	11 grams	1050 kg	0 kg	396,23 liters	3,12 kg CO_2eq/m^3
Industrial aggregate 4-8	310 kg	1,00%	31 grams	310 kg	310 kg	83,11 liters	1,26 kg CO_2eq/m^3
Medium Gravel 6-14	165 kg	1,00%	2 grams	165 kg	0 kg	62,26 liters	0,49 kg CO_2eq/m^3
Superplastificizer additive	3,40 liters		0 grams	4 kg	0 kg	3,21 liters	5,51 kg CO_2eq/m^3
Mapecube 1	6,00 liters		0 grams	7 kg	0 kg	5,31 liters	3,21 kg CO_2eq/m^3
Aqueduct	240,00 liters		26 grams	240 kg		240,00 liters	
A/C max	0,40						
Total water	240,00 liters	Check chloride content	1200 grams	2375 kg/ m^3	344 kg/ m^3	1000,59 liters	381,40 kg CO_2eq/m^3
		Chloride content	309 grams				
Air incorporated	20 Liters	Check chloride content	Verify	% by weight of recycled		14,49%	

Table 4. Specifications and environmental impact of the optimized R50/25 mix

Table 4 validates the effectiveness of the chemical optimization strategy. By substituting a portion of cement with a high-performance admixture, the mix achieves a lower carbon profile without altering the fundamental physical characteristics required for production.

A comparison of the two mixes shows that:

- 40 kg of cement was reduced from the initial 640 kg (-6.25%).
- The percentage of recycled content decreased by 0.16% because the cement contains a 5.70% recycled content.
- Indirect emissions from raw material production decreased by 5.25%.

A comparison of the resulting particle sizes of the mixes was also performed. Given the modest variation in dosages, no significant differences were noted between the two curves; they are practically identical.

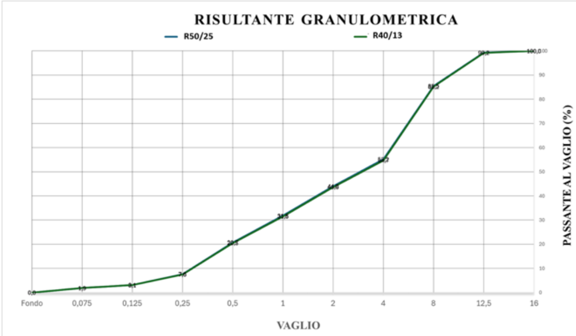

Figure 10. Comparative granulometric curves of standard (R40/13) and optimized (R50/25) mixes

Figure 10 illustrates the superposition of the granulometric curves for the reference mix (R40/13) and the optimized mix (R50/25). The substantial overlap confirms that the modification of the binder dosage did not alter the overall aggregate skeleton, thereby preserving the particle packing density and the workability of the fresh concrete.

3.2.1 Mix pillar

R4/19

Raw material	Quantity [kg-Liters]	Humidity	Chlorides	weight	recycled	Volume and mix	GWP production
CEM II B-M (P-LL) 42,5 N FINTITAN	360 kg		144 grams	360 kg	21 kg	114,29 liters	220,68 kg CO_2eq/m^3
sand 0-6	1090 kg	6,00%	11 grams	1090 kg	0 kg	411,32 liters	3,24 kg CO_2eq/m^3
Industrial aggregate 0-4	120 kg	1,00%	12 grams	120 kg	120 kg	32,17 liters	0,49 kg CO_2eq/m^3
Medium Gravel 6-14	730 kg	1,00%	7 grams	730 kg	0 kg	275,47 liters	2,17 kg CO_2eq/m^3
NRG Dynamon 1012 (s)	3,20 liters		0 grams	3 kg	0 kg	3,02 liters	5,19 kg CO_2eq/m^3
Aqueduct	162,00 liters		18 grams	162 kg		162,00 liters	
A/C max	0,45						
Total water	162,00 liters	Chloride content	192 grams	2465 kg/ m^3	141 kg/ m^3	1018,27 liters	231,76 kg CO_2eq/m^3
	chloride limit value	720 grams					
Air incorporated	20 Liters	Check chloride content	Verify	% by weight of recycled		5,70%	

Table 5. Detailed mix design composition and GWP analysis for R4/19 (Standard Pillar Mix)

The analysis of Table 5 clearly identifies cement as the **"carbon hotspot"** of the mixture. Scientifically, this demonstrates a **disproportionate relationship**: while cement constitutes only a small fraction of the total mass, it dictates nearly 95% of the Global Warming Potential (GWP). This confirms that the environmental impact of concrete is driven by the **chemical energy** embodied in the binder, not by the volume of inert materials. Therefore, the only viable engineering strategy to achieve significant environmental gains is to reduce the cement content, as optimizing aggregates would yield statistically insignificant results.

R5/25

Raw material	Quantity [kg-Liters]	Humidity	chlorides	weight	recycled	Volume mix	GWP production
CEM II B-M (P-LL) 42,5 N FINTITAN	330 kg		132 grams	330 kg	19 kg	104,76 liters	202,29 kg CO_2eq/m^3
Sand 0-6	1110 kg	6,00%	11 grams	1110 kg	0 kg	418,87 liters	3,30 kg CO_2eq/m^3
Industrial aggregate 4-8	100 kg	1,00%	10 grams	100 kg	100 kg	26,81 liters	0,41 kg CO_2eq/m^3
Medium Gravel 6-14	740 kg	1,00%	7 grams	740 kg	0 kg	279,25 litrers	2,20 kg CO_2eq/m^3
NRG Dynamon 1012 (s)	3,00 liters		0 grams	3 kg	0 kg	2,83 liters	4,87 kg CO_2eq/m^3
Mapecube 1 (s)	3,50 liters		0 grams	4 kg	0 kg	3,10 liters	1,87 kg CO_2eq/m^3
Aqueduct	148,50 liters		16 grams	149 kg		148,50 liters	
A/C max	0,45						
Total water	148,50 liters	Chloride content	177 grams	2436 kg/ m^3	119 kg/ m^3	1004,11 liters	214,93 kg CO_2eq/m^3
	chloride limit value	660 grams					
Air incorporated	20 Liters	Check chloride content	verify	% by weight of recycled		4,88%	

Table 6. Specifications and environmental impact of the optimized R5/25 pillar mix

The analysis of Table 6 demonstrates the efficacy of the chemical optimization approach. Even in structural elements like pillars, where safety margins are critical, it is possible to decouple the cement content from mechanical performance. The result is a more sustainable material that reduces CO_2 emissions without requiring changes to the production infrastructure or the aggregate supply chain [1].

These intervals were selected to monitor early strength development and long-term performance. The underlying assumption is that strength should improve over time; if the modified mix fails to reach target strength levels at any stage, it will not be suitable for practical application [1].

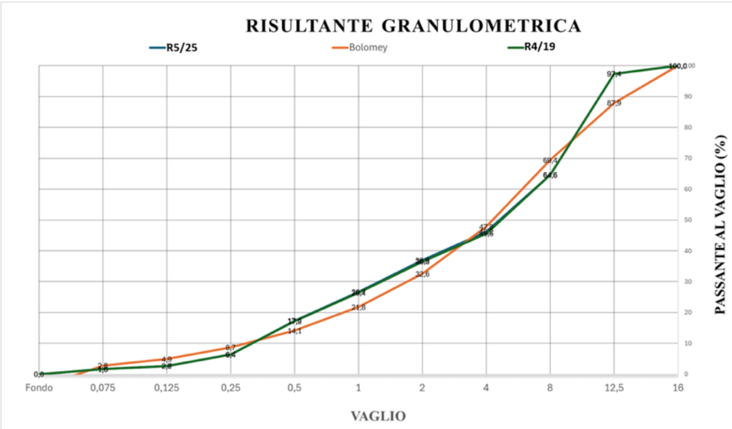

Figure 11. Comparative granulometric curves of standard (R4/19) and optimized (R5/25) pillar mixes

Similarly to figure 10, figure 11 compares the particle size distribution of the standard pillar mix (R4/19) versus the optimized version (R5/25). The curves demonstrate that the granulometric continuity is maintained. This validates that the reduction in cement content does not compromise the volumetric stability or the rheological properties required for casting.

3.3 Methodology

Factory Tests

Field tests were useful for verifying that the mixes (current and modified) were indeed similar in terms of consistency, but above all in terms of mechanical strength. Specifically, for the cupel mix, the tests were conducted over two days: on the first day, the current R40/13 mix was poured, observing the consistency of the concrete and taking three samples to prepare the specimens for compression tests at intervals of 1,7, and 28 days, thus constructing the strength-time correlation curve. The following day, the R50/25 mix (new mix) was poured, verifying that the consistency had not changed and taking three more samples of concrete to prepare the specimens [1]. The tests, visual for consistency and with the mechanical press for compressive strength, yielded satisfactory results:
The tables below present the compressive strength test results. For each mix and curing age, two cubic specimens were tested to ensure data reliability. The parameters are defined as follows:

- P (kN): Maximum load recorded at failure.

- R (MPa): Individual compressive strength (Resitance) of the specimen.
- Rm (MPa): Mean compressive strength (Resistenza Media), calculated as the average of the two samples (R1 and R2)

R40/13	Casting	20/05/2025

Data evidence	GG Maturation	P1	P2	R1	R2	Rm
21/05/2025	1	2,37	2,39	26,51	30,6	28,555
27/05/2025	7	2,442	2,374	43,22	51,95	47,585
17/06/2025	28	2,384	2,391	51,68	56,87	54,275

Table 7. Comparative compressive strength for standard concrete

R40/13 with MAPECUBE 1	Casting	21/05/2025

Data evidence	GG Maturation	P1	P2	R1	R2	Rm
22/05/2025	1	2,447	2,442	29,31	26,73	28,02
28/05/2025	7	2,421	2,428	50,17	46,7	48,435
18/06/2025	28	2,47	2,47	69,26	68,21	68,735

Table 8. Comparative compressive strength for concrete with Mapecube1

As it can be seen from compering two tables one standard concrete and the other with Mapecube1, when the amount of cement reduced it expected the resistance go low while in contrary it gained more resistance [1].

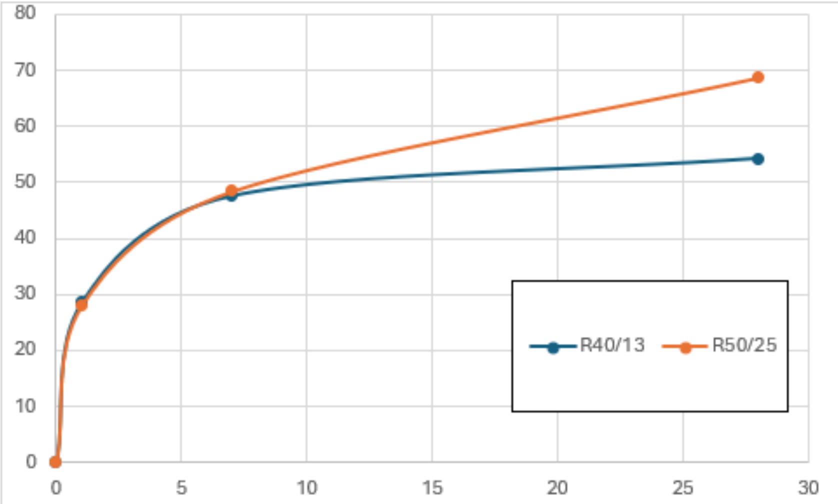

Figure 12. Compressive strength development over time

Here the blue line shows us the normal mix, and the orange line shows mix with Mapecube1. Looking at the results, we can see that on the first day, the concrete treated with Mapecube1 had slightly lower strength than the standard mix, approximately 1.88%. This small difference is to be expected, as the increase in initial strength can be influenced by the admixture's interaction with other components [1].

By the seventh day, the performance of the improved mix had not only improved but had even slightly surpassed that of the standard concrete, with an improvement of 1.79%. This is a promising sign that the admixture is starting to show its benefits even in the short term [1].

The most significant result was obtained on day 28. In this case, the Mapecube1 mix achieved a compressive strength of 68.74 MPa, more than 26% higher than the control mix. This significant improvement demonstrates that the admixture not only promotes early strength development but also has a significant impact on long-term performance [1].

In summary, the improved mix met and even exceeded mechanical strength expectations over the long term. This confirms that using Mapecube1 does not compromise concrete quality; on the contrary, it improves it. From a practical standpoint, this makes the new mix a reliable choice for structural elements requiring high resistance over time [1].

It is also important to note that compressive strength is significantly influenced by the water/cement ratio. A higher ratio typically results in lower strength due to greater porosity. Therefore, careful control of water content during mixing is essential [1].

Another factor that influences performance is aggregate size. Oversized aggregates can cause inadequate compaction and localized weaknesses, especially in precast elements with thin cross-sections. Therefore, choosing aggregates of the appropriate grain size ensures better distribution and overall strength [1].

Furthermore, the relationship between compressive strength and concrete age can be visualized using a standard growth curve. On this curve, compressive strength increases rapidly in the first few days and then gradually stabilizes, reaching a plateau. This behavior confirms the need for adequate curing periods to allow the material to reach its full potential [1].

For the column mix, compression tests were not performed for the three-time intervals, as was the case for the cupels; instead, only one sample was taken to prepare the specimens to be tested over the following 28 days. The test data are reported below [1].

DATA	MIX	P1	P2	R1	R2	Rm
20/05/2025	R5/25	2,512	2,513	81	79,9	80,45

Table 9. Mechanical test results (Load and Compressive Strength)

It is possible to note that the resistance is well above the 50 MPa design value. The average resistance of the current R4/19 mix is approximately 74 MPa, which allows us to state that the new column mix (R5/25) also guarantees the expected mechanical resistance [1].

3.4 Analysis of environmental impacts

In this section, we will analyze how the environmental impacts, expressed in tons of CO_2 eq, change following the introduction of the new cement-reducing additive and the resulting reduction in cement. Compared to the original mixes, a new raw material has been introduced, resulting in an additional CO_2 load in the environment, both due to its production and its upstream transportation. The addition of this additive also results in a reduction in cement dosage [1]. This reduction has a positive environmental impact in several respects:

- Lower CO_2 emissions from cement production used to produce the same volume of concrete
- Lower CO_2 emissions from cement transportation to produce the same volume of concrete

The analysis will be based on a balance of indirect emissions (raw material production and upstream transportation) expressed in tons of CO_2eq, before and after the mix modification. We will therefore analyze the indirect emissions of only the raw materials that undergo a change in dosage [1].

To determine the indirect emissions for raw material transportation, we must define the emission factors for transportation and supply distances [1].

Emission factors:

0.00049279 Ton CO2 eq/km road transport up to 7.5 tons (additive)

0.00091726 Ton CO2 eq/km road transport up to 33 tons (cement and aggregates)

0.00000353 Ton CO2 eq/ton * km Sea transport (cement)

Greenhouse gas conversion factors are taken from:

https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

Supply distances:

- Additives: 190 km
- Natural aggregates: 57 km
- Cement: 490 km by road, 730 km by sea.

Average weight transported per delivery:

- Natural aggregates: 32 tons
- Additives: 3,500 liters
- Cement: 32 tons (by road)

Calculation of emissions incidence expressed in $kgCO_2eq$ due to the transport of one Kg or liter of raw material:

- Additives: 0.49279 $kgCO_2eq$ /km*190km/3500 liters= 0.027 $kgCO_2eq$ /liters
- Aggregates: 0. 91726 $kgCO_2eq$ /km*57km/32000kg = 0.002 $kgCO_2eq$ /kg
- Cement (rubber): 0.91726 $kgCO_2eq$ /km*490km/32000kg =0.014 $kgCO_2eq$ /kg
- Cement (ship): 0.00353 kgCO2 eq/ton * km *730 km /1000= 0.002 $kgCO_2eq$ /kg

We report the declared emissions (GWP phases A1-A3) by the manufacturers for the production of product units:

Raw material	GWP (phases A1-A3)	Unit of measurement
Cement - CEM II/BM (P-LL) 42.5 R	613	$kgCO_2eq$./ton
Natural aggregates	2,97	$kgCO_2eq$./ton
Mapecube1	0.474	$kgCO_2eq$./kg
Industrial aggregate	4,08	$kgCO_2eq$./ton
Superplastificizer additive	1,530	$kgCO_2eq$./Kg

Table 10. Declared Global Warming Potential (GWP) values (Phases A1-A3) for raw materials

Table 10 lists the GWP for the environmental assessment. As expected, cement represents the most significant source of CO_2 emissions, while the impact of aggregates is nearly negligible. Including the exact GWP for the *Mapecube* admixture is necessary to verify that its addition does not negatively offset the environmental benefits gained from lowering the cement content.

3.4.1 Comparison of R40/13-R50/25 dosages

	R40/13	R50/25	
Raw materials	Quantity [kg-Liters]	Quantity [kg-Liters]	Difference [kg-Liters]
CEM II B-M (P-LL) 42,5 N FINTITAN	640 kg	600 kg	40 kg
Sand 0-6	990 kg	1050 kg	-60 kg
Industrial aggregates 4-8	310 kg	310kg	0 kg
Medium Gravel 6-14	165 kg	165kg	0 kg
Superplastificizer additive	3,40 liters	3,40 liters	0 kg
Mapecube1		6 liters	-6 liter

Table 11. Calculation of the Global Warming Potential (GWP) R40/13 vs R50/25

Once all the input data is known, it is possible to calculate the emissions balance per cubic meter of concrete produced.

3.4.1.1 Transport

Raw material	Difference [kg-Liters]	Difference in emissions from road transport [$kgCO_2/m^3$]	Difference in emissions from shipping [$kgCO_2/m^3$]	Total emissions difference [$kgCO_2/m^3$]
CEM II B-M (P-LL) 42,5 N FINTITAN	40 kg	0.562	0,103	0,665
Sand 0-6	-60 kg	-0.098		-0,098
Mapecube1	-6,00 liters	-0,160		-0,160
Total				0,406

Table 12. Calculation of the Global Warming Potential (GWP) R40/13 vs R50/25

From an initial analysis on transport, the environmental impact is less than 0,406 $kgCO_2/m^3$.

3.4.1.2 Production of raw materials

Raw materials	Difference [kg-Liters]	GWP (phases A1-A3) [$kgCO_2/m^3$]
CEM II B-M (P-LL) 42,5 N FINTITAN	40 kg	24,52
Sand 0-6	-60 kg	-0,178
Mapecube 1	-6,00 liters	-3,22
Total		21,13

Table 13. environmental impacts of raw material production per cubic meter of concrete R40/13 vs R50/25

The environmental impacts of raw material production per cubic meter of concrete produced are also positive, with emissions saved amounting to 21.13 $kgCO_2/m^3$.
Overall, emissions saved per cubic meter of concrete produced amount to 21,53 $kgCO_2/m^3$ [1].

3.4.2 Comparison of dosages R4/19-R5/25

	R4/19	R5/25	
Raw material	Quatity [kg-Liters]	Quantity [kg-Liters]	Difference [kg-Liters]
CEM II B-M (P-LL) 42,5 N FINTITAN	360 kg	330 kg	30 kg
Sand 0-6	1090 kg	1110 kg	-20 kg
Industrial aggregate 4-8	120 kg	100 kg	20 kg
Medium Gravel 6-14	730 kg	740 kg	-10 kg
Superplastificizer additive	3,20 litri	3,00 liters	0,20 liters
Mapecube 1		3,50 liters	-3,50 liters

Table 14. Detailed composition comparison between the reference R4/19 vs R5/25

Once all the input data is known, it is possible to calculate the emissions balance per cubic meter of concrete produced.

3.4.2.1 Transport

Raw material	Difference [kg-Liters]	Difference in emissions from road transport [$kgCO_2/m^3$]	Difference in emissions from shipping [$kgCO_2/m^3$]	Total emissions difference [$kgCO_2/m^3$]
CEM II B-M (P-LL) 42,5 N FINTITAN	30 Kg	0,42	0,077	0,5
Sand 0-6 - Medium Gravel 6-14	-30 Kg	-0,049		-0,05
Industrial aggregate 4-8	20 Kg	0,033		0,033
Superplastificizer additive	0,20 liters	0,005		0,005
Mapecube1	-3,5 liters	-0,094		-0,094
Total				0,394

Table 15. Calculation of the Global Warming Potential (GWP) R4/19 vs R5/25

From an initial analysis on transport, the environmental impact is less than 0,394 $kgCO_2/m^3$.

3.4.2.2 Production of raw material

Raw material	Difference [kg-Liters]	GWP (phases A1-A3) [$kgCO_2/m^3$]
CEM II B-M (P-LL) 42,5 N FINTITAN	30 kg	18,39
Sand 0-6 Medium Gravel 6-14	-30 kg	-0,089
Industrial aggregate 4-8	20 kg	0,082
Superplastificizer additive	0,20 liters	0,32
Mapecube 1	-3,5 liters	-1,88
Total		16,83

Table 16. Calculation of the Global Warming Potential (GWP) R4/19 vs R5/25

The environmental impacts of raw material production per cubic meter of concrete produced are also positive, with emissions saved amounting to 16,83 $kgCO_2/m^3$.

Overall, emissions saved per cubic meter of concrete produced (pillars) amount to 17,22 $kgCO_2/m^3$.

R4	kg/m^3 (dosage)	GWP (A1-A3) [kg CO_2/ton]	$kgCO_2eq/m^3$ (A1-A3)	$kgCO_2/m^3$ (transport road)	$kgCO_2/m^3$ (transport ship)	Total transport $kgCO_2/m^3$
Cement	360	613	220,68	5,059	0,927	5,988
Sand	1090	2,97	3,24	1,780		1,781
Medium gravel	730	2,97	2,17	1,192		1,193
Industrial aggregate (Dima)	120	4,08	0,49	0,196		0,196
NRG (liters)	3,2	1530	5,19	0,085		0,086

TOTAL (A1-A3)	231,76	TOTAL TRANSPORT	9,24
TOTAL CO2 eq EMISSIONS FOR PRODUCTION AND SUPPLY OF RAW MATERIALS PER CUBICLE OF CONCRETE [kg CO_2eq/m^3]		241,01	

Table 17. Total Global Warming Potential (GWP) calculation R4

Emission of CO_2 equivalent for 1 m^3 of concrete (R4) for production raw material and transport of this is 241,01kg CO_2 eq/m^3.

By using 17.22 kg CO_2 eq/m^3, the mix R4 produced 7.15% less emissions compared to the reference one.

R40	kg/m^3 (dosage)	GWP (A1-A3) [kg CO_2/ton]	Kg CO_2 eq/m^3 (A1-A3)	kg CO_2/m^3 (transport road)	kg CO_2/m^3 (transport ship)	total transport kg CO_2/m^3
Cement	640	613	392,32	8,99	1,65	10,64
Sand	990	2,97	2,94	1,62		1,62
Medium gravel	165	2,97	0,49	0,27		0,27
Industrial aggregate (Dima)	310	4,08	1,26	0,51		0,51
NRG (liters)	3,4	1530	5,51	0,09		0,09
TOTAL(A1-A3)		402,53	TOTAL TRANSPORT			13,13
TOTAL CO_2 eq EMISSIONS FOR PRODUCTION AND SUPPLY OF RAW MATERIALS PER CUBICLE OF CONCRETE [kg CO_2eq/m^3]				415,66		

Table 18. Total Global Warming Potential (GWP) calculation R40

Emission of CO_2 equivalent for 1m^3 of concrete (R40) for production raw material and transport of this is 415,66 kg CO_2 eq/ m^3 [1].

The modified mix R40 results in 5.18% lower CO_2 emission per cubic meter corresponding to 21.13 kg CO_2 eq/m^3 [1].

Considering that approximately 1100 m^3 of R40/13 and approximately 4,000 m^3 of R4/19 were produced in 2024, the CO_2eq savings would have been:

mix Table. 19	M^3	CO_2eq trasp.[$KgCO_2/m^3$]	CO_2 prod[$KgCO_2/m^3$]	CO_2 TOT[$kgCO_2$]
R40/13-R50/25	1100	0,406	21,12	23685,37
R4/19-R5/25	4000	0,394	16,83	68899,82
TOTAL				92585,19

Table 19. Total estimated annual CO_2eq savings based on 2024 production volumes for Coppelle and Pillar mixes

An analysis of the prices of raw materials and new dosages shows higher costs:
Cost analysis for MIX

MIX	DIFFERENCE (%)
R40	+2,31%
R50	
R4	+0,04%
R5	

Table 20. Economic analysis: Cost comparison

From an economic perspective, the introduction of the new additive led to increase in annual cost production, respectively €2,761 and €120 for R40 and R4 mix [1].

These additional costs are largely offset by the substantial environmental advantages obtained through the reduction of CO_2 emissions [1].

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4. Green energy solar panels and data analysis related to optimization

4.1 Objective

The primary objective of this chapter is to analyze the energy consumption profile of the plant for the reference year 2024, specifically assessing the impact of the photovoltaic system and the new methane reduction strategy on overall CO_2 emissions. The analysis focuses on the three main energy vectors utilized at the facility: electricity (sourced from both the national grid and the non-storage PV system for production lines), natural gas (used for artificial curing), and diesel (employed for logistics). To enable a standardized comparison across these distinct fuel types and evaluate their relative environmental weight, all specific consumption units (kWh, Scm, and liters) are converted into a single equivalent metric: the Ton of Oil Equivalent (TEP) [1].

4.2 Analysis of energy management

Before analyzing the consumption data, it is crucial to outline the strategic rationale behind the integration of photovoltaic (PV) technology, which rests on three fundamental pillars. The primary objective is Environmental Sustainability, achieved by generating on-site renewable energy to drastically lower reliance on the fossil-fuel-based grid and minimize indirect CO_2 emissions. Simultaneously, the company prioritizes Economic Efficiency, viewing the installation not as a compliance cost but as a 'Smart Investment' where operational savings and grid sales effectively outweigh amortization expenses. Finally, the system ensures greater Energy Independence; by installing a 434 kWp array, the facility satisfies a significant portion of its daily demand internally, thereby mitigating vulnerability to external market fluctuations. [1].

4.2.1 Analysis of energy consumption

Based on the available historical data, we analyze the consumption trends of the three primary energy vectors for the triennium 2022–2024. All measurements are standardized in Tonnes of Oil Equivalent

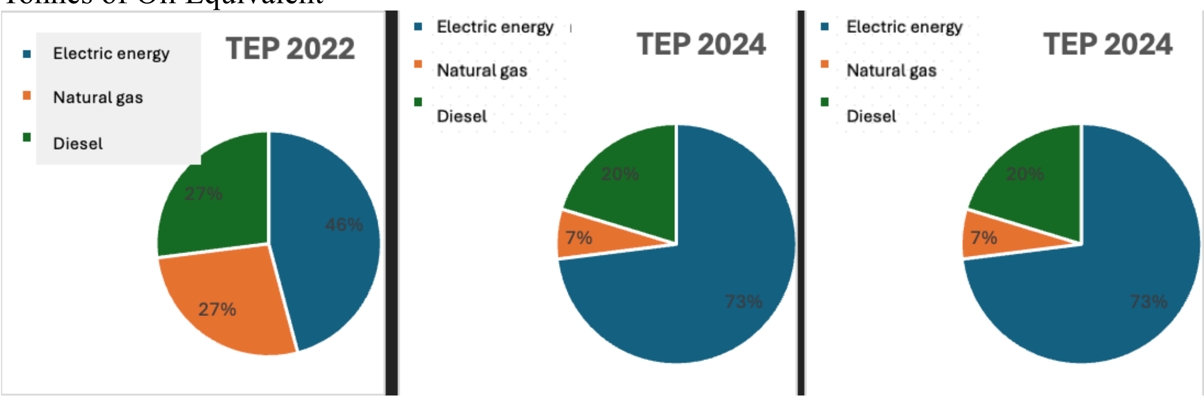


Figure 13. Trend of annual energy consumption (2022–2024)

The three pie charts illustrate the progressive transformation of the company’s energy portfolio from 2022 to 2024 [1].

As can be seen energy mix heavily reliant on fossil fuels. Natural gas and diesel combined for 54% of the total energy consumption (27% each) %. This indicates a production process that was significantly dependent on thermal energy and internal combustion engines [1].

A major structural shift occurred in 2023. the share of natural gas has sharp decrease from 27 to 7 percent, driven by optimization of concrete curing process. Consequently, electricity became the dominant energy vector, rising to 68% of the total mix [1].

We can witness that compony moving towards the electrification in 2024. Electricity now constitutes 73% of total energy requirement. Meanwhile, the share of diesel has remarkable decreased to 20%, reflecting the strategic decision to outsource logistics [1].

Energy Vector	Consumption				TEP			%TEP		
	UdM	2022	2023	2024	2022	2023	2024	2022	2023	2024
Electtric energy	kWh	538345,3	351925,01	521564,3	123,8	80,9	120,0	46%	68%	73%
Natural gas	Smc	89508	9582	13439	73,4	7,9	11,0	27%	7%	7%
Diesel	liters	80861	33344	36951,7	72,9	30,1	33,3	27%	25%	20%
TOTAL TEP					270,1	118,9	164,3			

Table. 21 results of the energy consumption in 2022-2023-2024

Based on the pie charts above and table2 in the year of 2022 electricity was the main source of energy contained 46% of portion. As it clears from pie chart related to 2024 this amount increased by 73% and become main source of energy supply for company. It shows that company was successful in reducing natural gas and diesel [1].

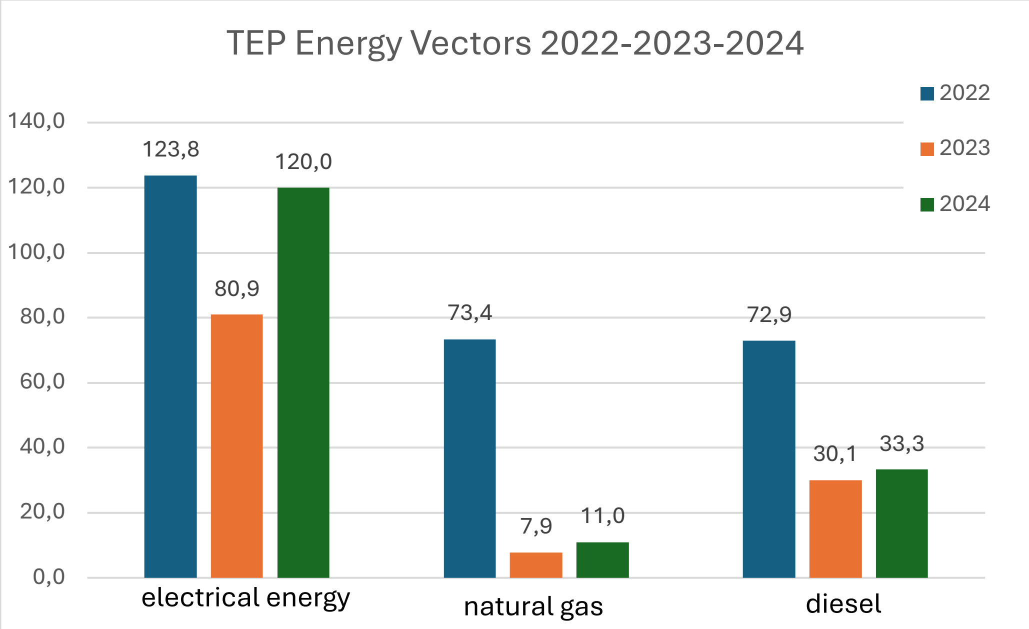


Figure 14. TEP Energy Vectors 2022-2023-2024

Table 21 and figure 14 show the energy consumption of three main sources, namely electricity, natural gas and diesel, for both plants(stab1+stab2) in 3 years, 2024, 2023, 2022 [1].

Based on the bar chart in 2024, the share of electricity usage was dominant, while natural gas decreased successfully along the way with decreasing diesel. As the table related to this bar chart illustrates that there is remarkable reduction of TEP from 2022 to 2024 which shows how effective system works [1].

Electricity consumption	2022 (kWh)	2022 (TEP)	2023 (kWh)	2023 (TEP)	2024 (kWh)	2024 (TEP)
January	60365	13,9	50770,0	11,7	45666,5	10,5
February	64942	14,9	52021,0	12	45065,1	10,4
March	61622	14,2	42991,0	9,9	36749,3	8,5
April	49554	11,4	16628,0	3,8	38574,3	8,9
May	48552	11,2	20167,0	4,6	43464,8	10
June	38103	8,8	15959,5	3,7	40070,8	9,2
July	34784	8	15430,0	3,5	45062,8	10,4

August	17844,3	4,1	11333,4	1,4	27722,3	6,4
September	34483	7,9	22590,3	3,1	39929,1	9,2
October	33579	7,7	39554,1	5,8	54335,6	12,5
November	45598	10,5	30809,3	5	54109,4	12,4
December	48919	11,3	33671,4	6	50814,3	11,7
Total	538345,3	123,8	351925,0	73,4	521564,3	120

Table 22. electricity consumption in 2022-2023-2024 (both plants)

This is the most important criterion, as it ensures high efficiency in energy management and pollution reduction. As can be seen, electricity consumption decreased from 2022 to 2023, due to the reduction in concrete production in 2023 and, consequently, the reduction in TEP for electricity consumption.

Consumption Natural gas	2022 (Smc)	2022 (TEP)	2023 (Smc)	2023 (TEP)	2024 (Smc)	2024 (TEP)
January	33498	27,47	3360	2,8	2808	2,3
February	39394	32,30	2778	2,3	298	0,2
March	14315	11,74	1485	1,2	3444	2,8
April	107	0,09	95	0,1	450	0,4
May	-1	0	19	0	4	0
June	0	0	18	0	1	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	255	0,21	0	0	2	0
October	-131	-0,11[1]	0	0	90	0,1
November	391	0,32	680	0,6	2279	1,9
December	1680	1,38	1147	0,9	4063	3,3
Total	89508	73,40	9582	7,9	13439	11

Table. 23 Natural gas consumption in 2022-2023-2024 (both plants)

As shown in table 23, natural gas consumption was high in January, February and March 2022. Following the implementation of appropriate production planning strategy, the objective of production planning strategy, the objective of reducing artificial maturation was achieved, resulting in a consequence decrease in methane consumption [1].

[1] Negative value following a consumption adjustment carried out by the natural gas supplier

consumption diesel	2022 (liter)	2022 (TEP)	2023 (liter)	2023 (TEP)	2024 (liter)	2024 (TEP)
January	10181	9,2	3042	2,7	2769	2,5
February	13055	11,8	4502,5	4,1	2272,5	2
March	10330	9,3	4013	3,6	1781,5	1,6
April	6441	5,8	3392,5	3,1	2847	2,6
May	7341	6,6	3780	3,4	3323	3
June	8030	7,2	3359	3	3273,5	3
July	9141	8,2	1434	1,3	4381	4
August	3305	3	987,5	0,9	1577	1,4
September	4340	3,9	2175	2	3480	3,1
October	3255	2,9	2901	2,6	4405	4
November	3125	2,8	2238	2	3841,2	3,5
December	2317	2,1	1519,5	1,4	3001	2,7
Total	80861	72,9	33344	30,1	36951,7	33,3

Table. 24 Diesel consumption in 2022-2023-2024 (both plants)

Diesel consumption has decreased following the outsourcing of the transportation of finished products to the assembly site [1].

Cubic meters of concrete produces	Total 2022	Total 2023	Total 2024
	m^3	m^3	m^3
m^3 of concrete produced in stab.1	14.216	12.411	14.271
m^3 of concrete produced in stab.2	8.114	2.339	3.393
Total m^3 of concrete produced	*22.331*	*14.750*	*17.664*

Table 25. concrete productions in 2022, 2023, 2024

Above, we report the volume of concrete produced in cubic meters over the last three years to compare consumption per unit of production expressed in cubic meters of concrete produced. Energy consumption is not actually proportional to production volume. However, this parameter provides a comparison between energy sources over the years [1].

Energy vector	TEP			TEP/mc CLS		
	2022	2023	2024	2022	2023	2024
Energia elettrica	123,8	80,9	120,0	0,0055	0,0055	0,0068
Gas naturale	73,4	7,9	11,0	0,0033	0,0005	0,0006
Gasolio (diesel)	72,9	30,1	33,3	0,0033	0,0020	0,0019
TOTALE TEP	270,1	118,9	164,3	0,0121	0,0081	0,0093
TOTAL mc concrete	22330,6	14750,3	17663,6	-	-	-

Table 26. Annual consumption of energy per concrete production

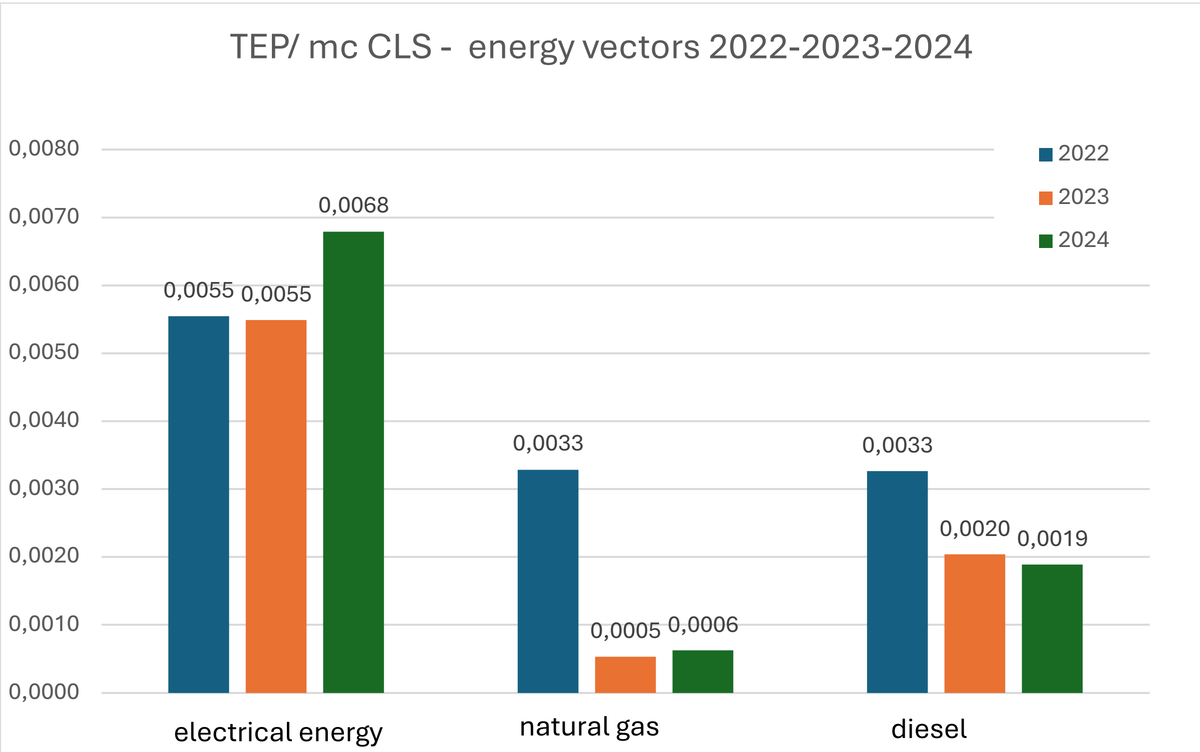


Figure 15. TEP/ mc CLS - energy vectors 2022-2023-2024

Table 26 shows how energy consumption has varied over the years based on production. A clear decrease in natural gas and diesel consumption is evident [1].

We can see drastic reduction in natural gas the specific consumption of natural gas collapsed from 0,0033 to 0,0006 TEP/m^3. This was gained through strategic production planning, which minimized the reliance on artificial curing during winter months [1].
Diesel consumption decreased from 0.0033 to 0.0019 TEP/mc, primarily due to the decision to outsource the transport of finished products to third-party providers [1].
Blue bar in 2022 in front of green bar in 2024 for diesel (gas olio) we see decrease due to the outsourcing reason. Before the factory trucks had the responsibility of transporting data but now the third party take this responsibility, so it won't be in our calculation anymore [1].
It can be understood from this bar chart that while the electricity becomes the dominant energy vector, the plant has successfully reduced its reliance on carbon-intensive fuels (gas and diesel) per unit of the product [1].

4.2.2 electricity consumption details

To reduce the environmental impact of energy consumption, the company has invested in the installation of two photovoltaic systems for the production and subsequent self-consumption of energy from renewable sources [1].

space and the greatest exposure to direct sunlight:
in industrial factories, the largest available surface is roof of sheds and production halls.
The concept of solar panel (photovoltaic) involves directly capturing light of the sun and converting it into electricity which we introduced this section earlier. This process is based on physical phenomenon called photovoltaic effect [1].

According to standards and given the nature of a large production site like Truzzi S.p.A. photovoltaic systems are typically installed in the location with the most available

In this paragraph we will analyze in detail the electricity consumption of the last three years and we will delve into the consumption of the reference year (2024).

total electricity consumption EE (kWh)			
period	2022	2023	2024
January	60365	50770	45666,5
February	64942	52021	45065,1
March	61622	42991	36749,3
April	49554	16628	38574,3
May	48552	20167	43464,8
June	38103	15959,5	40070,8

July	34784	15430	45062,8
August	17844,3	11333,4	27722,3
September	34483	22590	39929,1
October	33579	39554,1	54335,6
November	45598	30809,3	54109,4
December	48919	33671,4	50814,3
total	538345,3	351925	521564,3

Table. 27 electricity consumption details in each month

Based on the table.27 electricity consumption was high in 2022 while it reduced drastically in 2023 it shows that this decrease is directly correlated to the lower volume of concrete production during that year. An important thing to notice here is photovoltaic system did not change the demand of electricity usage but only it change the source of energy consumption it can be concluded that the reduction of electricity consumption was only related to volume of concrete produced [1].

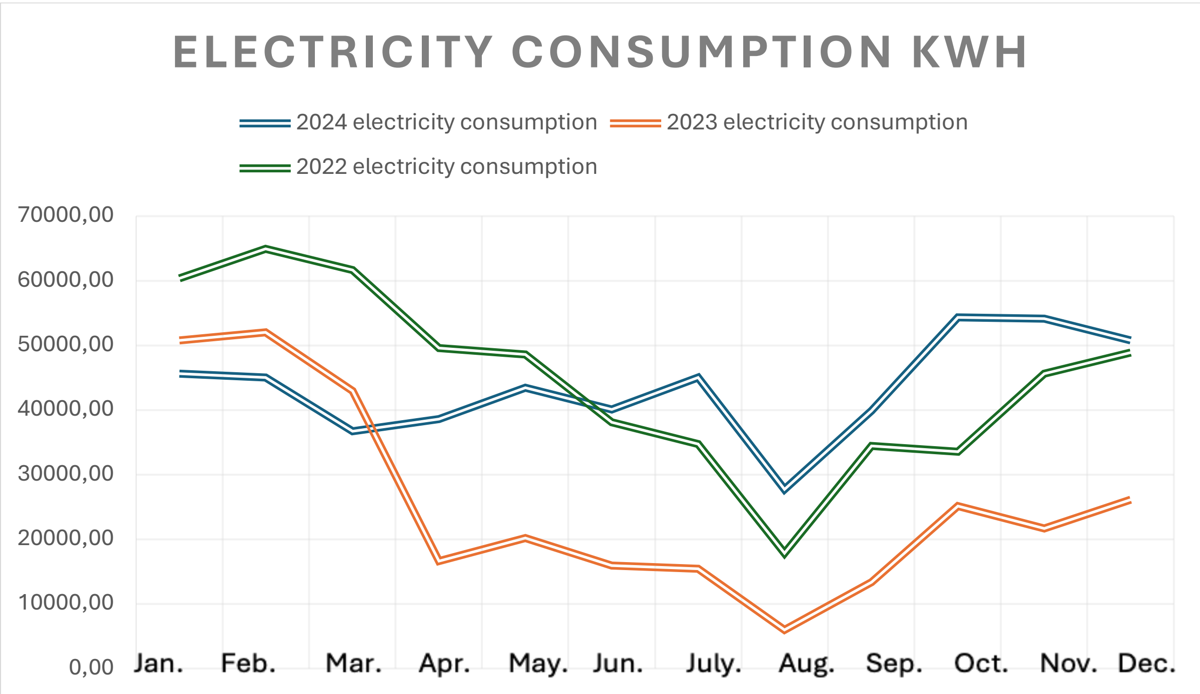


Figure 16. Electricity consumption kWh

The graph above illustrates the total electricity consumption trends across the three-year period (2022-2024).

As observed in graph and table.27, there was a sharp decrease in electricity demand in 2023 compared to 2022. This reduction is related to lower volume of concrete production recorded during that year. While in 2024 consumption levels returned to values similar to 2022, reflecting the recovery in production volumes [1].

We should pay attention here that installation of photovoltaic panels did not alter the facility's total energy demand. The machinery continues to require the same amount of energy to operate. The PV system simply changed the source of this energy—shifting a portion of the supply from the national grid to self-generated renewable energy—without reducing the actual gross consumption of the factory [1].

Electricity data plant1 2024	plant 1: national network	Plant1: photovoltaic			Total consumption
		Produced	sell	consumption	
Months	kWh	kWh			kWh
January	19263,2	9232,4	2926,6	6305,8	25569,0
February	19132,2	11018,6	4082,1	6936,5	26068,7
March	13049,4	19387,0	10924,9	8462,1	21511,5
April	12248,9	26256,5	14579,7	11676,9	23925,8
May	12260,5	31507,8	17912,3	13595,5	25856,0
June	10730,2	30762,5	10079,8	20682,7	31412,9
July	9224,4	36640,0	12547,2	24092,8	33317,2
August	5100,5	17510,0	5972,9	11537,1	16637,6
September	16581,6	21530,0	9720,5	11809,5	28391,1
October	25052,1	11120,0	3736,9	7383,1	32435,2
November	26689,7	7989,0	2278,0	5711,0	32400,7
December	25232,7	7678,0	3101,0	4577,0	29809,7
Total	194565,4	230631,7	97861,9	132769,9	327335,3

Table 28. total consumption of electricity energy in plant1

Based on the table.28 we are talking about the electricity produced by photovoltaic system in company. The process is like this; the system produces electricity and use it inside the factory process and when this amount of production goes beyond the need of factory the excess amount will sell to national grid due to absence of battery storage. This process happens during production and consumption of electricity. As it is obvious from table first column is related to national network that the company use it as energy source then we have photovoltaic panels that help company to use their own production, there are three columns in photovoltaic part Produced, sell and consumption [1]. Produced refers to production of electricity by photovoltaic system in factory site. Sell refers to excess amount of production to national grid and Consumption refers to usage of electricity produced by photovoltaic system which can be calculate by subtraction of produced from sell. This table give information only on plant1. Total amount sold to national grid is 97861,9 kWh. Further total energy consumption can be calculated by summing the national network energy consumption and energy consumption of photovoltaic system. Total consumption for plant1 is 327335,3 kWh [1].

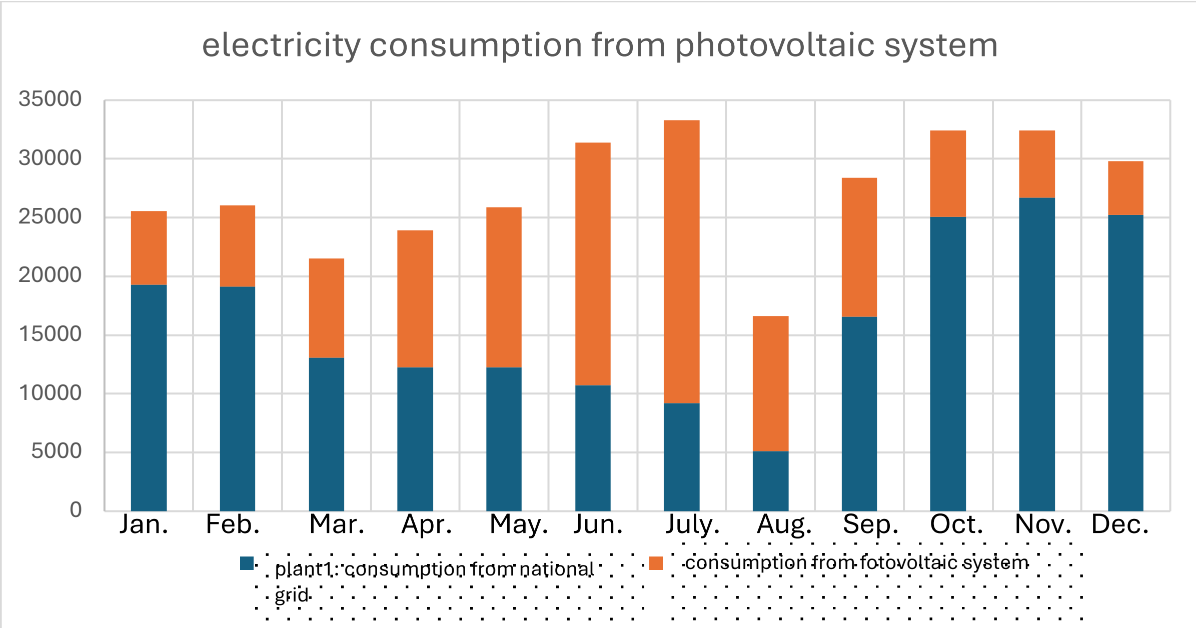


Figure 17. Electricity consumption from photovoltaic system plant1

This bar chart shows the electricity consumption from photovoltaic system that stated with orange color and color blue is related to amount of electricity sold to national grid [1].

Electricity data plant2 2024	plant 2: national network	Plant2: photovoltaic			Total consumption
		Produced	sell	consumption	
Months	kWh	kWh			kWh
January	14759,5	7453,6	2115,5	5338,1	20097,6
February	13256,2	8980,7	3240,6	5740,2	18996,4
March	7956,4	16690,3	9408,9	7281,4	15237,8
April	6830,8	23549,1	15731,3	7817,7	14648,5
May	7417,3	29142,5	18951,0	10191,5	17608,8
June	6728,6	19570,5	17641,3	1929,3	8657,9
July	6528,4	25413,8	20196,6	5217,2	11745,6
August	5825,5	25701,8	20442,6	5259,2	11084,7
September	8787,8	13396,8	10646,6	2750,2	11538,0
October	16043,5	9588,3	3731,3	5857,0	21900,5
November	16751,9	7044,5	2087,7	4956,8	21708,7
December	17050,2	5801,7	1847,3	3954,4	21004,6
Total	127936,1	192333,7	126040,7	66293,0	194229,1

Table 29. total consumption of electricity energy in plant2

This table is similar to table.28 while the numbers related to plant 2, it can understand that the most production of electricity and sells belong to plant 2. Total amount sold from plant 2 is 126040,7. Now it can be declared that total electricity sold from both plants is 223902,6 kWh. And total consumption for plant2 is summation of energy consumption from national grid and energy consumption from photovoltaic system 194229,1 [1].

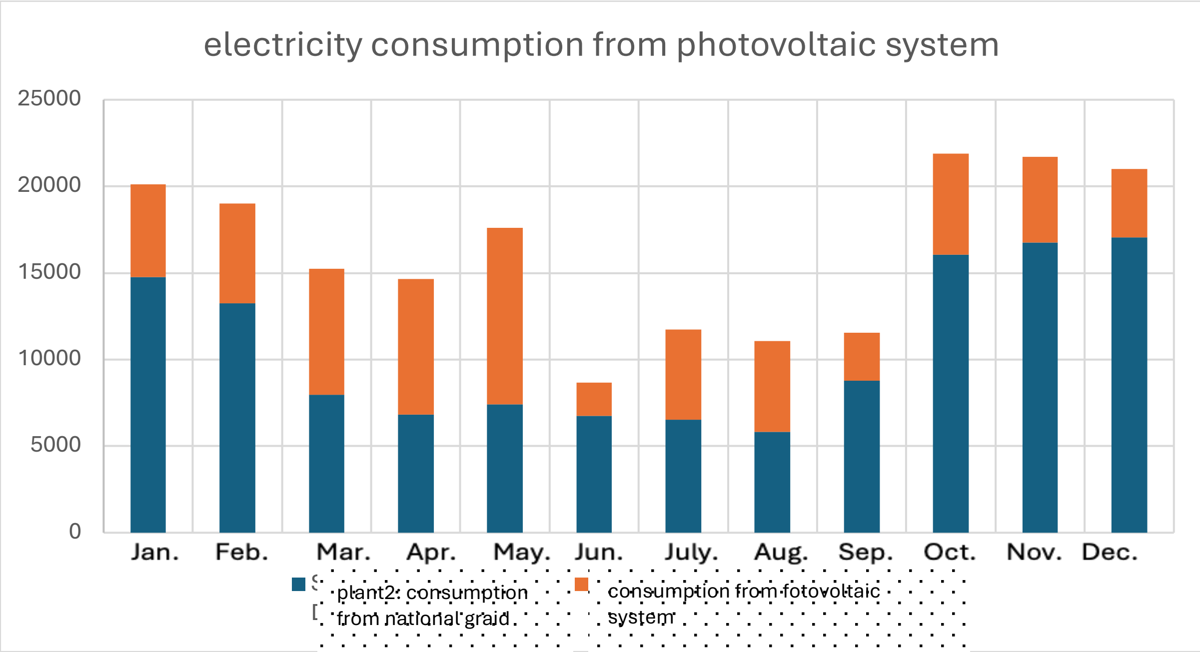


Figure 18. Electricity consumption from photovoltaic system plant2

Based on bar chart we can see the most consumption of plant2 related to October, November and December and it is reasonable because company produced more concrete in those months which result in more consumption of energy [1].

Electricity data plant 1 2024	Photovoltaic consumption plant1	Total consumed	% consumption from photovoltaic	Photovoltaic consumtion plant 2	Total consumed Plant2	%Consumption from photovoltaic
Months	kWh	kWh	%	kWh	kWh	%
January	6305,8	25569,0	24,7%	5338,1	20097,6	26,6%

February	6936,5	26068,7	26,6%	5740,2	18996,4	30,2%
March	8462,1	21511,5	39,3%	7281,4	15237,8	47,8%
April	11676,9	23925,8	48,8%	7817,7	14648,5	53,4%
May	13595,5	25856,0	52,6%	10191,5	17608,8	57,9%
June	20682,7	31412,9	65,8%	1929,3	8657,9	22,3%
July	24092,8	33317,2	72,3%	5217,2	11745,6	44,4%
August	11537,1	16637,6	69,3%	5259,2	11084,7	47,4%
September	11809,5	28391,1	41,6%	2750,2	11538	23,8%
October	7383,1	32435,2	22,8%	5857	21900,5	26,7%
November	5711,0	32400,7	17,6%	4956,8	21708,7	22,8%
December	4577,0	29809,7	15,4%	3954,4	21004,6	18,8%
Total	132769,9	327335,3	40,6%	66293	194229,1	34,1%
Overall total (plant1+plant2) 2024		Consumption from Photovoltaic (kWh)		Total Consumption (kWh)		% Photovoltaic Coverage
		199.062,9		521.564,4		38,2 %

Table 30. Consolidated photovoltaic energy balance (Plant 1 + Plant 2): Production, Self-consumption, and Grid Injection

Consumption from Photovoltaic (kWh)=132.769,9+66.293=199.062,9

Total Consumption (kWh)=327.335,3+194.229,1=521.564,4

% Photovoltaic Coverage percentage → Percentage = (Total Consumed/ Total Produced) × 100= 199.062,9/521.564,4 x 100 = 38,2%

Following the individual analysis of each production site, it is essential to evaluate the overall impact of photovoltaic systems on the company's total energy for the year 2024. When combined total electricity demand amounted to 521,564.4 kWh. And it shows that total self-consumption from photovoltaic plants successfully supplied 199.062 kWh directly to machinery and systems. This results in a consolidate Solar Energy Share of 38.2% this is an indicator demonstrating that more than one-third of the entire factory's energy requirement was met by on-site renewable generation. This achievement significantly reduces the company's reliance on the national grid and mitigates the environmental impact associated with purchasing conventional electricity [1].

electricity data plant1 2024	Photovoltaic consumption plant1	Total electricity produced plant 1	%Consumption from photovo	Photovoltaic consumption plant2	Total electricity produced plant2	%Consumption From photovoltaic
Months	kWh	kWh	%	kWh	kWh	%
January	6305,8	9232,4	68,3%	5338,1	7453,6	71,6%
February	6936,5	11018,6	63,0%	5740,2	8980,7	63,9%

March	8462,1	19387,0	43,6%	7281,4	16690,3	43,6%
April	11676,9	26256,5	44,5%	7817,7	23549,1	33,2%
May	13595,5	31507,8	43,1%	10191,5	29142,5	35%
June	20682,7	30762,5	67,2%	1929,3	19570,5	9,9%
July	24092,8	36640,0	65,8%	5217,2	25413,8	20,5%
August	11537,1	17510,0	65,9%	5259,2	25701,8	20,5%
September	11809,5	21530,0	54,9%	2750,2	13396,8	20,5%
October	7383,1	11120,0	66,4%	5857,0	9588,3	61,1%
November	5711,0	7989,0	71,5%	4956,8	7044,5	70,4%
December	4577,0	7678,0	59,6%	3954,4	5801,7	68,2%
Total	132769,9	230631,7	57,6%	66293,0	192333,7	34,5%
Total (plant1+plant2)		Total PV Consumed(kWh)		Total PV produced (kWh)		Self-consumption %
		199062,9		422965,4		47,1

Table 31. Calculation of avoided CO2eq emissions due to photovoltaic self-consumption (2024)

Total PV consumed (kWh)= 132769,9+ 66293=199062,9 kWh

Total PV produced (kWh) = 230631,7+ 192333,7= 422965,4 kWh

Percentage = (Total Consumed/Total Produced) × 100 = 199062,9/422965,4 x 100 = 47,1%

This shows that in 2024 photovoltaic plants generated a total of 422695,4 kWh of green energy. Of this total production, the facility was able to instantly consume 199062,9 for its internal operations. The result of self-consumption rate 47.1% this indicates that slightly less than half of generated solar energy is used on-site, while the remaining 52,9% is injected into the national grid. This ratio is due to the absence of a battery storage system. Solar production often peaks during weekends, or midday breaks when industrial consumption is lower, forcing the surplus energy to be exported rather than stored for later use. Operational insight: we said that 47.1% is company self-consumption and so 52.9% is injected into national grid. This ratio is due to the absence of Battery Energy Storage System (BESS). Solar production often peaks during weekends, or midday breaks when industrial activity is minimal. Without batteries to store this surplus energy, the system is forced to export the excess power to grid rather than saving for later use during peak operational hours. This is the reason that company may consider installing battery for saving photovoltaic energy in future [1].

Calculating emissions saving of electricity produced by photovoltaic systems	Photovoltaic consumption plant1	Photovoltaic consumption plant2	Total consumtion from photovoltaic	Tons of CO_2 eq saved
Months	kWh			Ton Co2eq
January	6305,8	5338,1	11643,8	2,645

February	6936,5	5740,2	12676,7	2,879
March	8462,1	7281,4	15743,5	3,576
April	11676,9	7817,7	19494,6	4,428
May	13595,5	10191,5	23787,0	5,403
June	20682,7	1929,3	22612,0	5,136
July	24092,8	5217,2	29310,0	6,657
August	11537,1	5259,2	16796,3	3,815
September	11809,5	2750,2	14559,7	3,307
October	7383,1	5857,0	13240,0	3,007
November	5711,0	4956,8	10667,8	2,423
December	4577,0	3954,4	8531,4	1,938
Totale	132769,9	66293,0	199062,8	45,2

Table 32. Calculating emissions saving of electricity produced by photovoltaic systems

This table illustrates in 2024, the amount of electricity consumption from photovoltaic system in each month. And in continue calculation of how much the system was effective in reduction of CO_2. First and second column shows the photovoltaic energy consumption separately and then after calculating the sum of the total energy consumption from photovoltaic panel. Last column illustrates saving CO_2 which calculated by official diffusion coefficient. It means the more consumption of solar panels, the less factory is forced to buy electricity from national grid, in conclusion less emission exist. Based on the table total consumption of two plant were approximately 199 thousand kilo watt hour and this is equivalent reducing 45 Tons of CO_2. All of this information stated here belongs 2024 [1].

Way of calculation of CO_2 saved in the year of 2024 is as follows:

The factor for conversion is taken from ''http://emissioni.sina.isprambiente.it/inventario-nazionale/'' and the number is 227,12 million g CO_2 eq/kWh. We multiply this factor by total photovoltaic consumption and dividing by 1000000 to get Ton CO_2eq.

4.2.2.1 Economic and Environmental Cost analysis

(due to the privacy numbers rounded)

Financial overview this section evaluates the economic sustainability of the photovoltaic installation for the year 2024. The analysis compares the annualized cost of the system against the financial benefits generated through energy savings and grid sales [1].

We have initial investment for both plants. Plant1 and plant2 are respectively 200000€ and 204000€ which amounts to 408600€. Based on useful life of 30 years, the annualized capital cost is 13000€ [1].

We have to know when we reach to ROI, Return On Investment. This important to us for multiple reasons, because it is the heart of management. First being Green it is not only related to cost, most of the managers thinks of solar panels as a luxury goods for preserving of environment and it is only an extra cost for company but here we can see it is not only an expensive goods with high cost but also it is a money making process. We show that yearly cost of system (approximatley 13000€) is much less than the money which system brings for us (approximately 91000 €). So this is a cleverly investment [1].

Return on investment, the system generated value in two ways:1. Avoided costs (self-consumption) by using 199063 kWh of self-generated power, the company saved approximately 64000€ in electricity bills and 2. Direct revenue (grid sales): the sale of excess energy (220000 kWh) to the national grid generated an additional income of 26000€. It can be understood that total annual benefit is 91000€ [1].

Another important aspect that can be followed is environmental efficiency of this investment which needed the cost per ton CO_2 avoided. We calculated the cost incurred to avoid one ton of CO_2 emissions [1].

Total ton CO_2 avoided in 2024 is 45 Tons. Cost per ton calculated as 13000€/45 Ton = 300 € per ton CO_2 eq [1].

4.2.3 Methane consumption

From the table below we can see the consumption in Smc of methane from 2022 to 2024

Natural gas consumption	2022 (Smc)	2023 (Smc)	2024 (Smc)
January	33498	3360	2808
February	39394	2778	298
March	14315	1485	3444
April	107	95	450
May	-1	19	4
June	0	18	1
July	0	0	0
August	0	0	0
September	255	0	2
October	-131[2]	0	90
November	391	680	2279
December	1680	1147	4063
Total	89508	9582	13439

Table 33. Natural gas consumption

Table.33 gives a comparative analysis of natural gas consumption in standard cubic meter across three years [1].

In 2022 consumption followed a typical seasonal trend peaking drastically during winter months (January-March) due to the reliance on artificial curing. The total annual consumption stood at 89 thousand Smc [1].

In 2023, the company implemented a strategy to reduce methane emissions. This strategy involves two main actions:

1. Using higher-performance cements and cement-reducing additive
2. Rotating production formwork

2.3.2 Use of higher-performance cements

During the winter, the natural curing of products is slower, and to compensate for this, the use of higher-performance cements arises. Higher-strength cements are used during winter, namely 52.5 cements instead of 42.5 [1].

The environmental impacts associated with the production of these cements are greater (higher GWP levels A1-A3), but they are dosed in smaller quantities per cubic meter of concrete. In 2024, the company introduced the use of cement reducing additives (Mapecube1)

[2] The negative consumption is due to recalculations by the methane supply service management company.

for the production of rooftiles and beams, which allowed for a further reduction in cement dosage compared to 2023 [1].

Cement	Plant1			plant2		
	m^3plant1	Dosage reduction (2024-2023)	Cement saved [kg]	m^3 plant2	Dosage reduction (2024-2023)	Cement saved [kg]
CEM II A-LL 52.5	4445,95	37,10	164938	104,3	33,75	3520
Total cement saved [kg]	164938			3520		
Total cement saved [kg]	168458					

Table 34. cement analysis in term of dosage

This table shows us by changing cement type how much we saved. CEM 52.5 (52.5 instead of 42.5) is the type of cement that we used to save more cement since this type is stronger and even less amount of it can give us good quality product. Dosage reduction tells us how much we used less compare to 2023 to 2024, in each cubic meter for preparing cement. Cement saved column gives information on that company produced around 168 thousand less, it caused drastic reduction in needs of transportation of cement which effect indirect CO_2 emission. Therefore, using less is the most effective way to reduce embodied product [1].

Saved CO_2		
Transport savings		
Average load weight	32	Ton
Number of avoided deliveris	5	Delivery
Distance per trip	86	Km

Total avoided distance	453	Km
Emission factor CO_2	0,00091726	Ton CO_2 eq/ Km
Avoided emissions CO_2	0,415271793	Ton CO_2 eq
Cement production savings		
Cement saved CEM 52,5	168	Ton
GWP (A1-A3) 52,5	0,86991	Ton CO2 eq/ Ton
Avoided emissions CO_2	147	Ton CO_2 eq

Table 35. relations of Total avoided distance vs Cement saved CEM 52,5 and Avoided emissions CO_2

Table 35 gives information CO_2 saving from 2 category aspect which is transport and cement production. By reducing the amount of cement to 168 ton we consequently reduce the number of transports. Another important point is that by reducing number of transports we reduce the use of diesel fuel. When we transport 168 ton less cement it means that we used 5 trucks less and we avoided 453km of commuting in this way we avoided 0,415-ton CO_2 emission. Therefore, by reducing cement we prevented the production of 147-ton emission into atmosphere [1].

Additional CO_2 emissions (transport of additive)		
Transport of additives		
Total additive volume	22751,25	liters
Average volume per delivery	3546	Liters/delivery
Number of deliveries	6,4	Delivery
Total delivery distance	1219,046108	km
Emission factor	0,00049279	Ton CO_2 eq/ km

Table 36. Additional CO_2 emissions (transport of additive)

From the data of table.36 it can be understood that total additive volume for producing concrete in 2024 were 22751 liters. In average in each transportation of this additive with truck it brought around 3500 liters. It means for supplying this additive during the year, around 6-7 times of commuting to factory. Therefore, the distance which trucks have driven is 1219 km. We witness that usage of additive (mapecube1) is the cause of a little bit of increase in pollution in transportation part but this increase in compare of huge amount of cement that we saved is nothing [1].

CO_2 emission	0,600733732	Ton CO_2 eq
Emission from additive production		
Total additive volume	22751,25	liters
Total additive mass	20,13	ton
GWP (A1-A3) MC1=MC60=MC60W	1,53	ton CO_2 eq/ ton
Total CO_2 emission	31	Ton CO_2 eq

Table 37. Emission from additive production

We can see that table.37 is related to pollution due to additive production, it means that pollution in supply place for producing additive. In previous table we saw unit in liters while in this table we can see it in ton the reason is that standard formula for environmental (GWP) assesses is based on weight. Production of additive is twice more pollutant than production of cement. This is a trade-off part we use a product which is more pollutant but in a very small amount. In return, this allows us to save a very large amount (168 ton) of a medium polluting material (cement) [1].

Reduction calculation			
Transport	Cement	-0,415271793	Ton CO_2 eq
	Additive	0,600733732	
Subtotal		0,185461939	
Production	Cement	-147	
	Additive	31	
Subtotal		-115,7384632	
TOTAL REDUCTION CO_2 eq		-115,5530013	

Table 38. Reduction calculation

Table 38 proves previous calculations to determine the final “net environmental impact” of 2024 strategy. It balances the savings (negative numbers) against the additional emissions (positive numbers). Although we saved trips for cement, the transport required for the chemical additives resulted in slightly higher transport emissions than those avoided. This increase is negligible in the broader context. Remarkable reduction in cement -147 tons offsets the carbon cost of producing the additive (+31 tons). Result is a total net reduction of 115.55 ton of CO_2 eq. this proves that the strategy of “using high performance materials to reduce volume” is highly effective [1].

production planning

A new production scheduling strategy has been adopted, whereby the formwork for product production is used on alternate days. This results in increased artificial curing time (one extra day) without resorting to artificial curing of products. In the company, a single product type can generally be produced in two different formworks, so by altering production days, no useful production days are lost [1].

28/11/22	HC 60x60/70	28/11/24	HC 60x60
29/11/22	HC 60x60	29/11/24	
30/11/22	HC 60x60	2/12/24	HC 60x60
1/12/22	HC 60x60	3/12/24	
2/12/22	HC 60x60	4/12/24	HC 40x60
5/12/22	HC 60x60	5/12/24	
6/12/22	HC 40x80	6/12/24	HC 40x60
7/12/22	HC 40x80	9/12/24	

Figure 19. Comparison between the production schedules for a formwork during the winter of 2022 and 2024

This image shows a comparison between the production schedules for a formwork during the winter of 2022 and 2024. It is possible to note that production in the same formwork is alternating. Methane use in 2024 was significantly reduced thanks to these two actions. Actual consumption is mainly due to heating the mixing water, heating the factory offices and in exceptional cases for the artificial curing of the products due to specific needs [1].
Also graph.11 provides a visual comparison of production for a specific formwork between the winters of 2022 and 2024. On the left side (2022), as can be seen dates are consecutive (28,29, 30…). To maintain this daily turnover in cold weather, the concrete had to be demolded rapidly (within 24 hours). Since natural curing is slow in winter, the facility was forced to use gas-fired steam curing to accelerate the hardening process artificially. On the other hand, in 2024 the dates showing alternating pattern, here we see strategic shift by allowing the concrete to rest in the mold for 48 hours instead of 24, the product utilizes the extended time to cure naturally. This “alternating day strategy” effectively leverages time as substitute for energy. By extending the retention time in the mold, it somehow eliminates the need for external gas heating without sacrificing overall production capacity [1].

	2022	2023		2024	
Natural gas consumption	Gas consumption for artificial curing and hot water				
Months	Smc	Smc	Difference vs % 2022	Smc	Difference vs % 2022
January	33044	3057	-91%	2459	-93%
February	39097	2495	-94%	38	-100%
March	14078	1322	-91%	3267	-77%
April	0	0	-	380	-
May	0	0	-	2	-
June	0	0	-	0	-
July	0	0	-	0	-
August	0	0	-	0	-
September	255	0	-100%	0	-100%
October	-255	0	-100%	53	-121%
November	391	542	39%	2010	414%
December	1388	900	-35%	3733	169%
Total	87998	8316	-91%	11942	-86%

Table 39. Gas consumption for artificial curing and hot water

Considering consumption in 2022 and 2024, in which the cubic meters of concrete produced are roughly similar, we can compare the methane consumption per cubic meter of concrete produced and therefore the emissions saved thanks to the strategies adopted.
To determine the tons of CO_2eq saved, we can use a conversion factor established by national bodies, such as ISPRA. The institute has set methane conversion factor for 2024 at 2.020 $kgCO_2eq/Sm^3$ [1].
Table.39 provides a month by month comparison of natural gas consumption across year 2022 and the optimized year which is 2024. The data revealss a structural change in facility's energy profile.
We have zero-consumption profile (summer) from April to September, gas consumption remains near zero. The data indicates a rise in consumption during November (2010 Smc) and December (3733 Scm) compared to the 2022. Despite the operattional needs in late 2024 the total annual consumption decreased from 87998 Scm to 11942 Scm, representing an overall 86% reduction in an overall 86% reduction in fossil fuel dependency [1].

	2022	2023	2024
Natural gas consumption	Gas consumption for artificial curing and hot water		

Months	Ton CO2eq	Ton CO2eq	Ton CO2eq
January	66,74888	6,17514	4,96718
February	78,97594	5,0399	0,07676
March	28,43756	2,67044	6,59934
April	0	0	0,7676
May	0	0	0,00404
June	0	0	0
July	0	0	0
August	0	0	0
September	0,5151	0	0
October	-0,5151	0	0,10706
November	0,78982	1,09484	4,0602
December	2,80376	1,818	7,54066

Table 40. Gas consumption for artificial curing and hot water

While table.39 analyzed the reduction in volume, table.40 quantifies the actual environmental impact in terms of Carbon Dioxide equivalent (Ton CO_2 eq). The most important point is the winter season. In 2022, the months of January and February alone were responsible for releasing over 145 Tons of CO_2 (66.7+78.9). On the other hand, during the same period in 2024, emissions were capped 5 Tons combined. Consequently, the facility's total carbon footprint related to natural gas collapsed from 177.76 Tons in 2022 to just 24.12 Tons in 2024. This represents a direct avoidance of approximately 153 Tons of CO_2 in single year. This achievement validates the premise that shifting from “Artificial Curing” to “Chemical/Tempral Curing” is the single most effective decarbonization strategy for the plant's thermal processes [1].

Total	177,75596	16,79832	24,12284
m^3 concrete	22331	14750	17664
TCO_2eq/m^3	0,0080	0,0011	0,0014
Diff. 2024-2022	-116,48 TCO_2eq		

Table 41. difference in production of emissions

Based on table 41, we face an important aspect which tell us that weather reduction of gas was only because of the reduction of production or not. This table proves that even if we consider production, the system became optimized. This table is crucial for validating the strategy, as it normalizes emissions against production volumes to calculate the specific carbon intensity. it can be considering the reduction in total emissions was partly due to lower production volumes in 2024 compared to 2022 (from 177.76 to 24.12). However, the “intensity” metric disproves this correlation. This represents an 82.5% reduction in specific emissions. It proves that the facility has successfully “decoupled” its carbon footprint from its production output. Even if production were to return to 2022 levels, the emissions would remain drastically lower due to the structural elimination of artificial curing. Based on this efficiency obtained the total calculated reduction for the reference period is 116.48 Tons of CO_2 eq [1].

Knowing the average costs of methane in the years 2022-2024, it is possible to determine the savings obtained by company implementing these strategies:

	2022		2023		2024	
	Gas consumption	Gas cost	Gas consumption	Gas cost	Gas consumption	Gas cost
	Smc	€	Smc	€	Smc	€
	89508	112584,96	9582	13320,55	13439	16103,68
Average Cost [€/Smc]	1,258 €/Smc		1,390 €/Smc		1,198 €/Smc	
Concrete production [m^3]	22331		14750		17664	
Average consumption[Smc/ m^3]	3,94 Smc/m^3		0,56 Smc/ m^3		0,68 Smc/ m^3	
Methane savings [Smc]	Reference year		-49808,15 Smc		-57665,12 Smc	
Economic savings of methane [€]			- 69.241,50 €		- 69.098,94 €	

Table 42. Cost analysis

Finally, it is possible to determine the cost ratio (negative, I have an indirect profit because we have not spent these sums)/ emissions
69098,94€/24,12284TCO_2eq= -2864,461354 €/ TCO_2eq

Here negative sign indicates that decarbonization was not a cost but a profit. For every single ton of CO_2 that company prevented from entering to the atmosphere the company effectively obtained 2 thousand euros in operational savings. This approved that the transfer from artificial curing to natural curing is a win-win scenario where maximum environmental benefit aligns with financial return [1].

Based on the analysis of table 23 we witness this table quantifies the economic savings achieved by eliminating natural gas from the curing process, comparing the 2022 against the 2024 optimized scenario. We can see the total expenditure on natural gas dropped remarkably. In 2022, cost of gas was € 112,854 on gas. In 2024, despite maintaining active production this cost fell to 16 thousand euros.

The final row, methane savings calculates the avoided cost. By applying the 2024 average gas price to avoided gas volume the strategy generated a net economic saving of 69 thousand euros in 2024 alone. This proves that the decarbonization strategy is financially robust [1].

5. Possible Circular Economy Action

5.1 Recovery of water

In the prefabrication industry, significant volume of water is generated daily from washing concrete mixers and transport trucks. Managing this "processed water" efficiently is a critical environmental challenge.

Thanks to measures implemented by this project, the environment and Truzzi S.p.A. will benefit from the results achieved, as water, energy and fossil fuel consumption will be reduced, as well as the waste produced by the company itself. All this translates into a simultaneous saving in operating costs. Before the interventions implemented, Truzzi S.p.A. used recycled water (i.e., process water derived from washing the mixers and the operating machines for transporting and pouring the concrete, and from the recovery of fresh concrete residues) to produce new concrete following filtration treatments. These treatments generated new waste, namely, filtration residues (fine sand mixed with cement particles), and consumption of electricity to operate the filter press (electricity directly powers the filter press and compressors, since several mechanisms are driven by compressed air) [1].

The interventions will allow the reused water to be reused as it is, without any type of treatment, thus eliminating:

- waste production (filtration residues)
- CO_2 emissions from heavy vehicles used to transport waste sent for recovery
- Electricity consumption for filtration
- The noise generated by compressors producing the compressed air needed to operate the filter press

5.2 Multiblock

In daily operations, generating "Fresh Residual Concrete" is unavoidable. This refers to the small amounts of wet concrete left inside the mixers after washing, or the surplus material returned in transport trucks after casting operations. Conventionally, this residue represents a burden: it must be washed out, collected, and eventually crushed and disposed as waste. While Truzzi S.p.A. transformed this operational inefficiency into a production opportunity through the Multiblock project. Instead of treating this fresh residue as waste, the company intercepts it before it hardens. The surplus concrete is poured into specialized steel molds to cure [1].

Here we have the "Lego" concept: the resulting product is a series of large, modular concrete blocks designed with a smart interlocking mechanism. It is much like giant "Lego" bricks, they feature pyramidal stud (male) and recesses (female) that allow them to be dry stacked safely and stably without need for mortar or binders. This innovation allows the facility to achieve 100% recovery of fresh concrete waste [1].

Description of the artifacts

Multiblock prefabricated elements, with standardized shapes and sizes, are produced for the construction of gravity retaining walls for embankments and loose materials of any kind, with heights greater than one meter, exploiting the elements' own weight for stability [1].

The specially designed geometric symmetries allow for a variety of assembly combinations between elements of the same series and different series, and along the two main directions of the blocks (see figures 9 and 10). Multiblock is made of vibrated reinforced concrete with a cubic compressive strength greater than 50 MPa. The main characteristic of the multiblock elements is the connection between the elements; this is ensured by concave and convex truncated pyramid-shaped square-based surfaces, distributed symmetrically and regularly on two opposite lateral surfaces [1].

Metal inserts, such as threaded bushings, are used to move the elements. They carry the required CE marking and have adequate load-bearing capacity to ensure safe handling during all phases of formwork removal, transport, and installation [1].

Below are the geometric and construction details of the elements in the different series: MB, MT and MS:

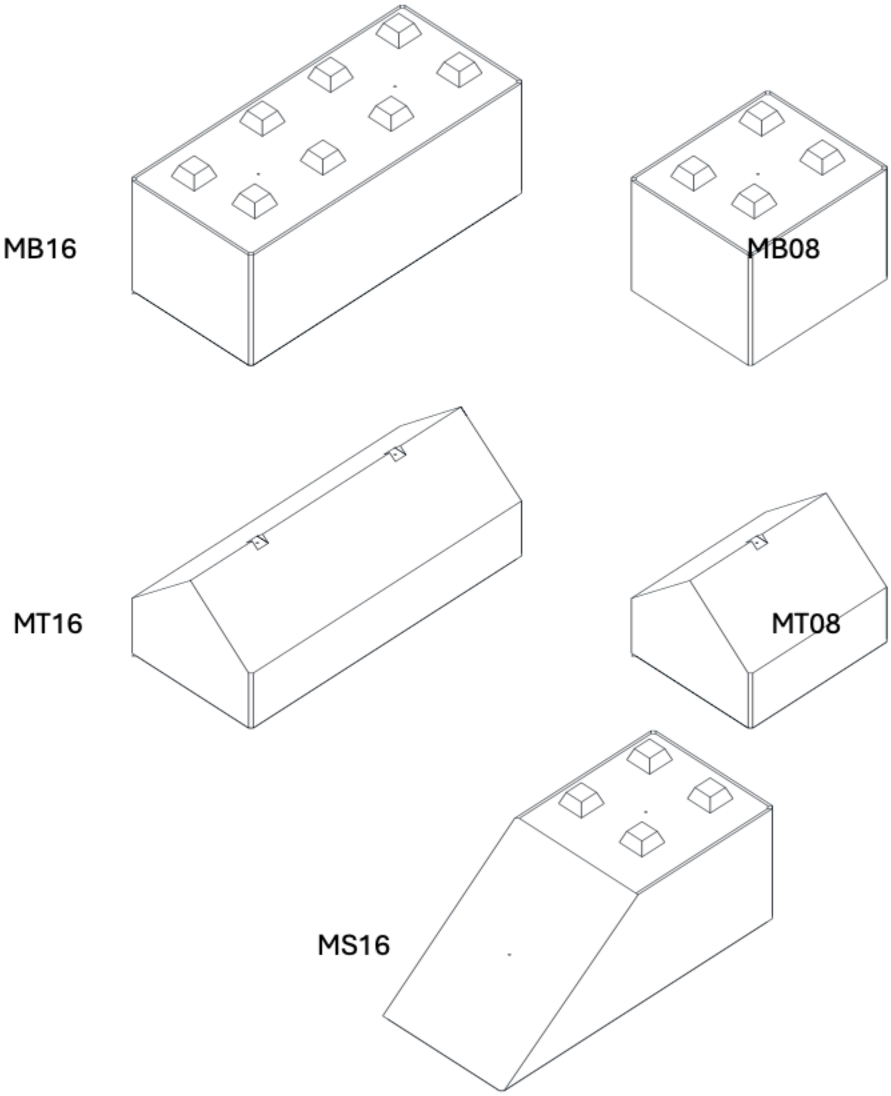
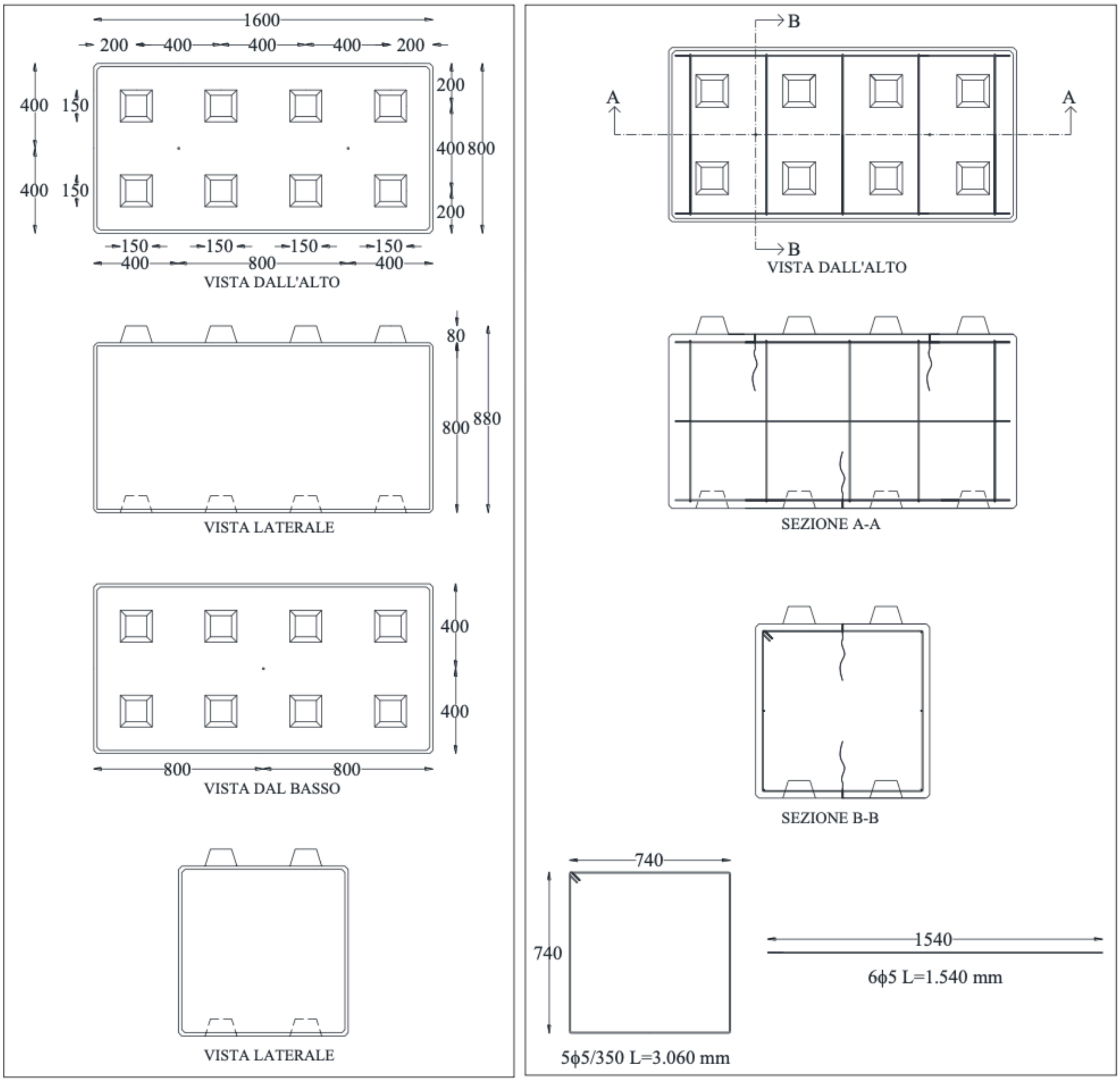


Figure 20

MB16-MB08

The MB series Multiblock element is a reinforced concrete element with a parallelepiped shape, featuring concave and convex truncated pyramidal shapes with a square base, distributed symmetrically and regularly on two opposite lateral surfaces to ensure interlocking the overlapping elements. The dimensions of the elements are shown in Figures 9 and 10, for the MB16 and MB08 products, respectively [1].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VISTA DAL BASSO
VISTA LATERALE
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A
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B
VISTA DALL'ALTO
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1540
6ϕ5 L=1.540 mm

Figure 21

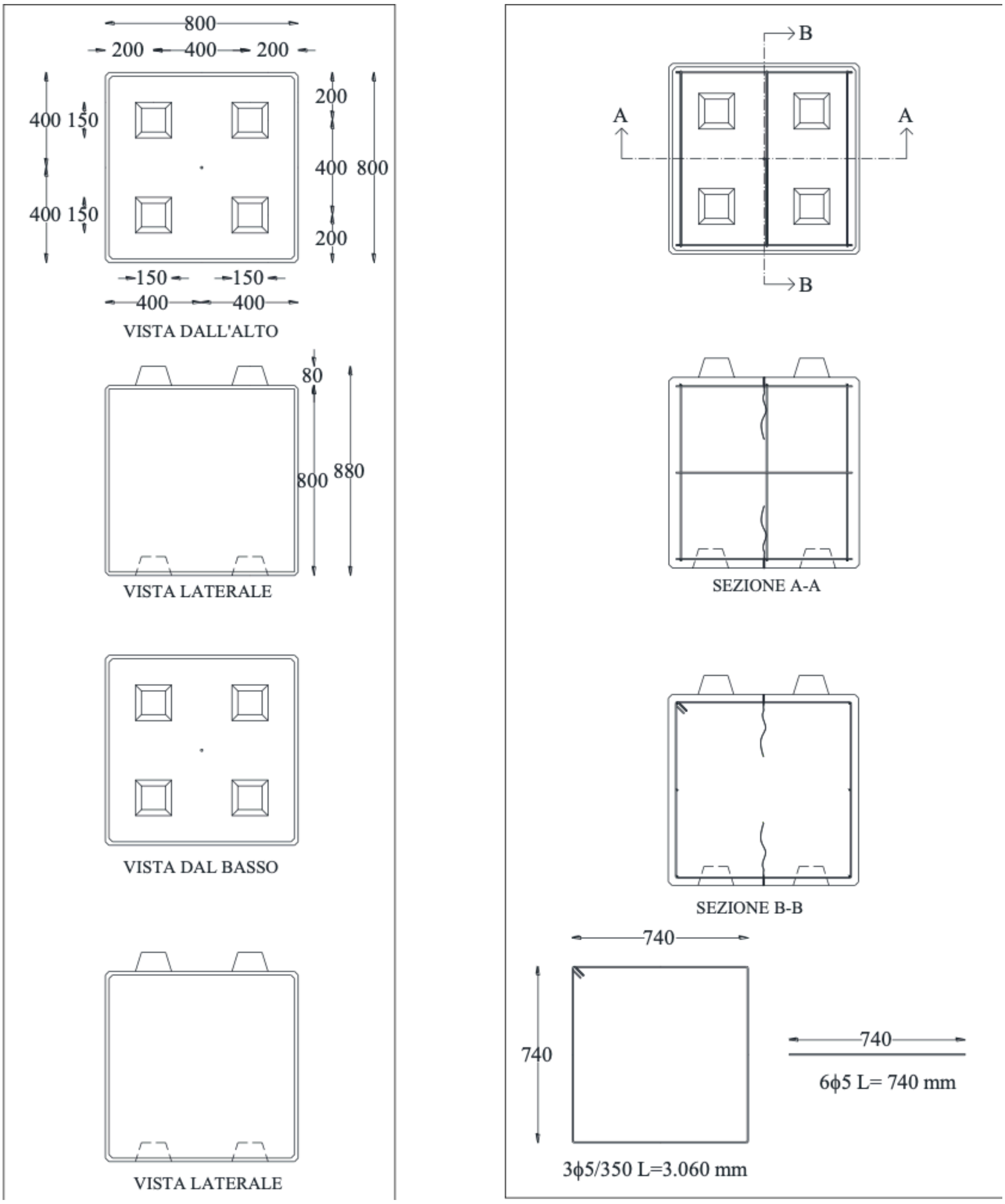


Figure 22

The Multiblock element from the MT series is also a vibrated reinforced concrete element that, unlike the previous elements, features only truncated pyramid-shaped convex sections with a square base on the lower surface to ensure constraints on the underlying elements. This element serves to complete the upper surface of a structure composed of Multiblock elements from the MB and MS series and therefore cannot be topped with other elements. The sloping top shape serves to protect against stagnant water or other substances that could impair the durability of the elements [1].

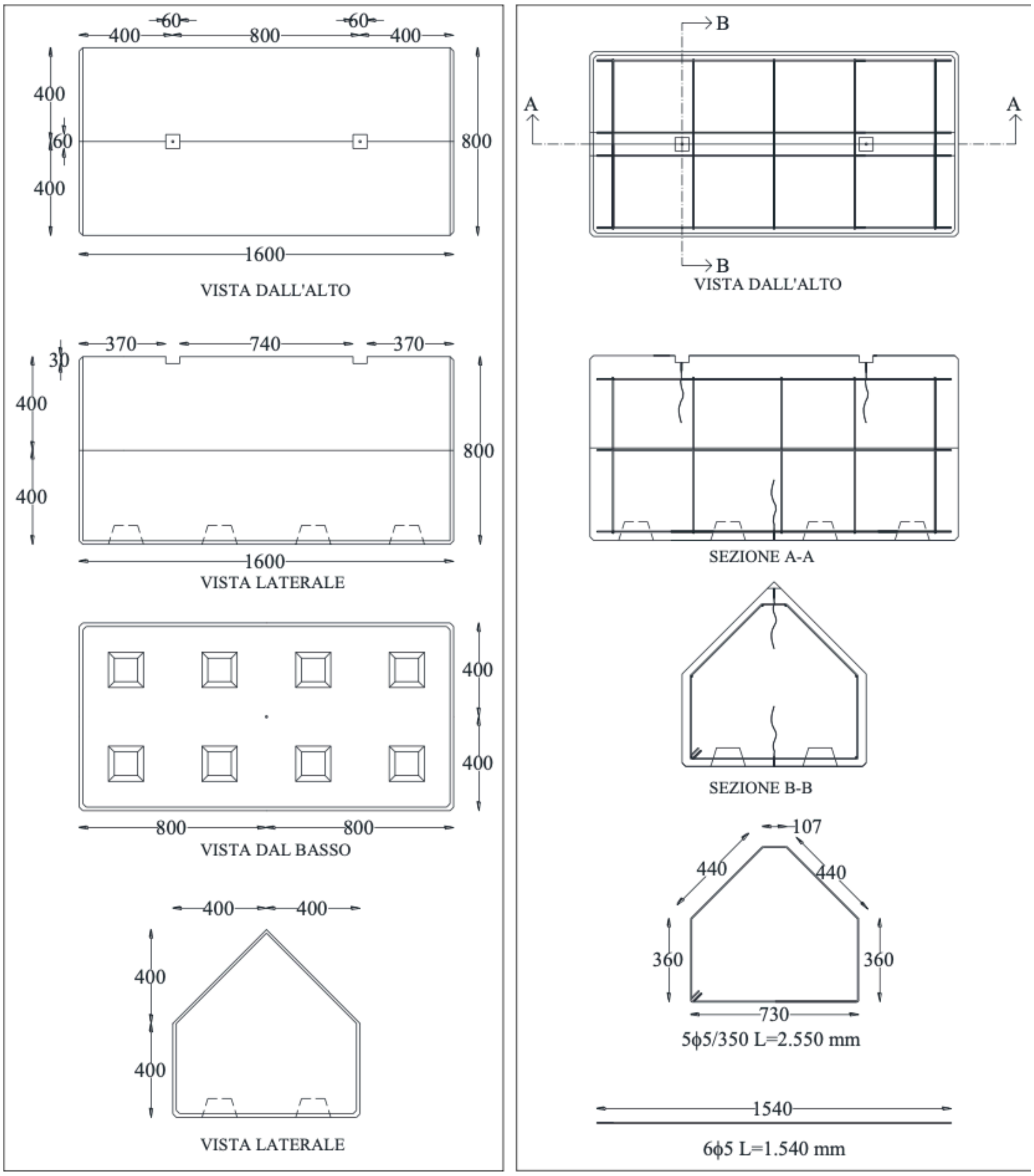
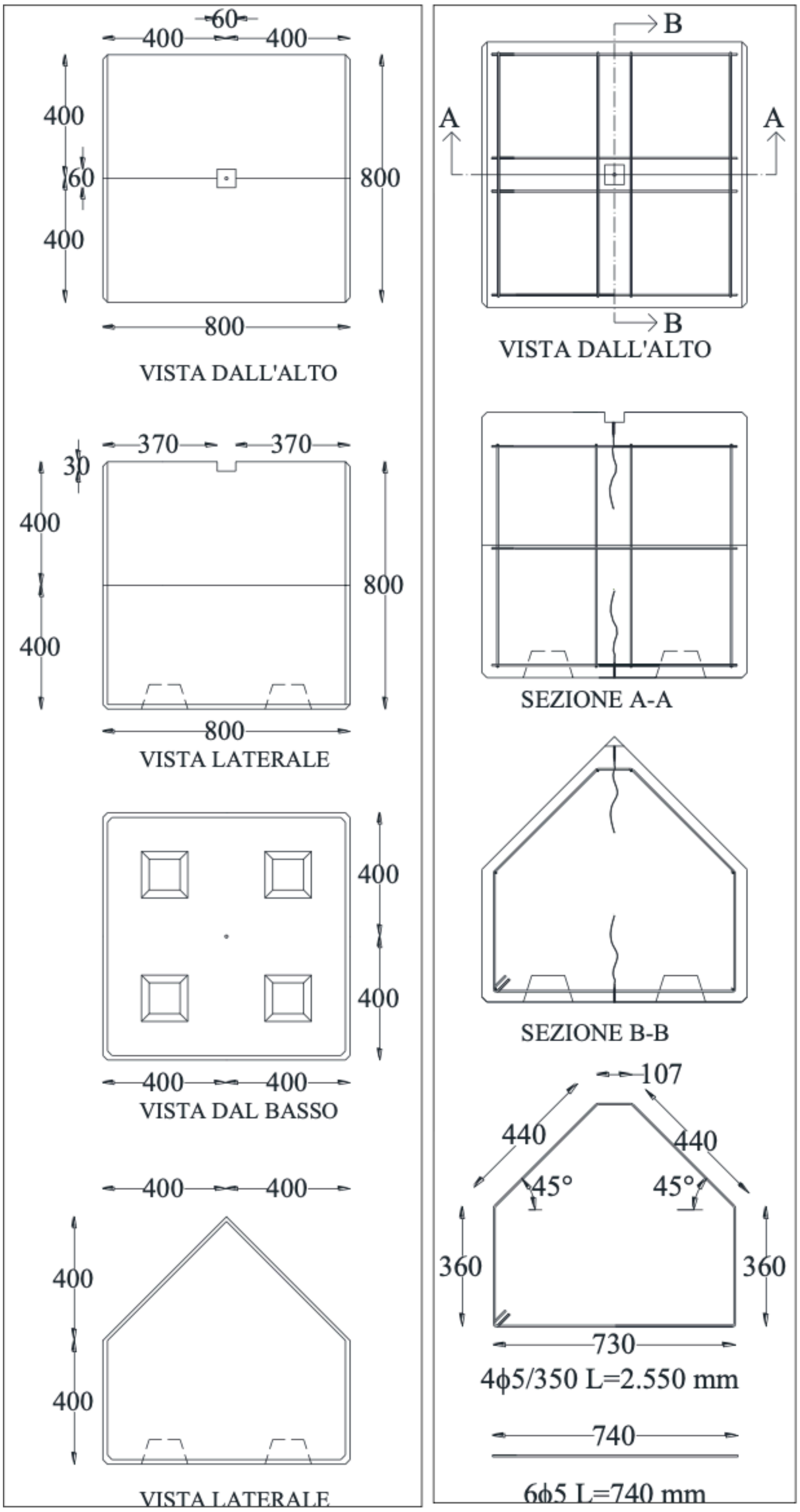


Figure 23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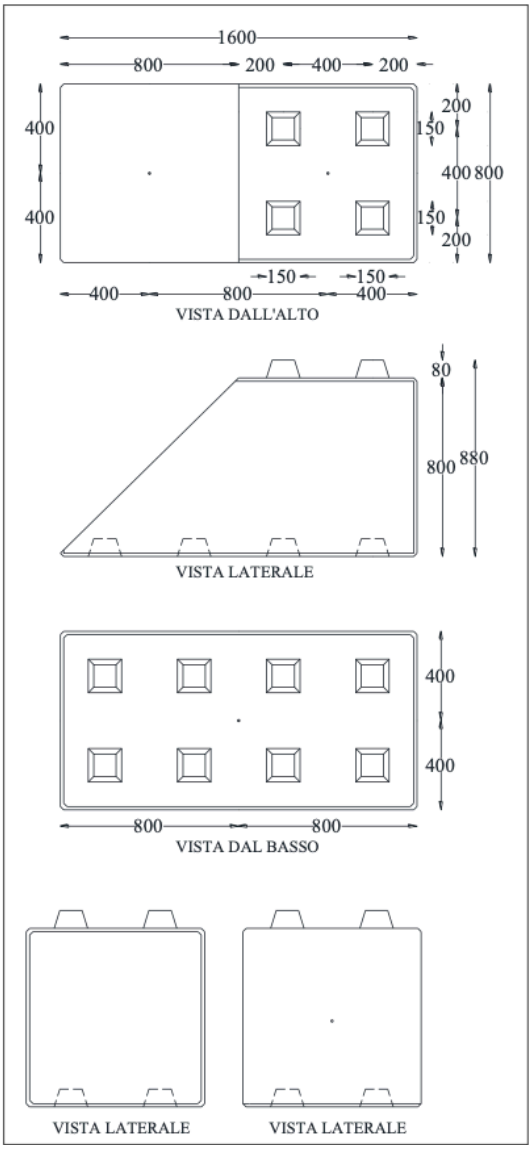
360
730
4ϕ5/350 L=2.550 mm
740
6ϕ5 L=740 mm

Figure 24

MS16

The MS series product allows for tapering of the end sections, both longitudinally and transversally, of a wall composed of Multiblock elements. The vibrated reinforced concrete element, unlike the MB series elements, features truncated pyramid-shaped convexities with a square base across the entire lower surface to ensure connection with the elements below and partially on the upper surface to ensure continuity of connections with the elements above [1].



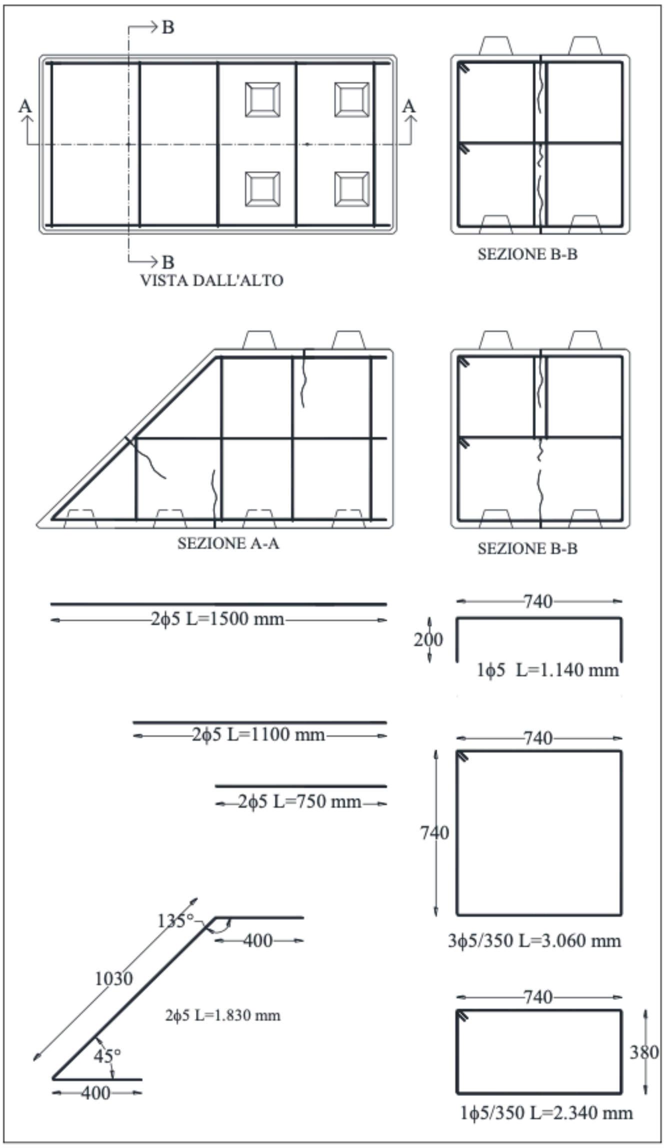


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Figure 25

REFERENCE STANDARDS

- UNI EN 13369:2018: Common rules for precast concrete products
- UNI EN 15258:2009: Precast concrete products elements for retaining walls
- UNI EN 206:2016: Concrete–specification, performance, production, and conformity
- UNI 11104:2016: Concrete-specification, performance, production, and conformity-supplementary specifications for the application on EN 206
- NTC 2018: Update of the “Technical standards for construction”.

Material characteristics

Concrete at 28 days

Cubic characteristic resistance	R_{ck}	50	MPa
Characteristic cylindrical resistance	f_{ck}	40	MPa
Partial safety factor for concrete	γ_c	1,5	-
Coefficient that takes into account long-term effects	α_{cc}	0,85	-
Mean value of cylindrical compressive strength	f_{cm}	48	MPa
Average value of axial tensile strength of concrete	f_{ctm}	3,5	MPa
Characteristic value of axial tensile strength (5% fractile)	$f_{ctk;0,05}$	2,5	MPa
Characteristic value of axial tensile strength (95% fractile)	$f_{ctk;0,95}$	4,6	MPa
Secant modulus of elasticity of concrete	E_{cm}	35220	MPa
Contraction strain in concrete at tension f_c	ε_{cl}	0,0020	-
Ultimate contraction strain in concrete	ε_{cu}	0,0035	-
Design compressive strength of concrete	f_{cd}	22,67	MPa

Design tensile strength of concrete	f_{ctd}	1,64	MPa
Permissible stress in concrete in the characteristic combination	$\sigma_{c,carat.}$	24	MPa
Allowable stress in concrete in quasi-permanent combination	$\sigma_{c,q.p.}$	18	MPa

Beyond the raw numerical data, this table serves a fundamental purpose: it provides a certified validation of the multiblock's structural integrity. It confirms that the concrete recovered from washing process is not a degraded by-product but rather retains the full properties of high-performance structural concrete. Essentially, the multiblock is physically identical in quality to facility's primary structural elements, such as beams and pillars, adhering to the same rigorous standards. Furthermore, the discrepancy shown between the characteristic strength and the design strength highlights the safety factors applied during engineering calculations. This intentional safety buffer ensures that the blocks possess a high margin of reliability against failure, even under unexpected loads. Finally, the elastic properties indicate that the elements are highly rigid, a critical feature for their primary function as gravity retains walls, ensuring they stand firm and resist deformation when holding back large volumes of soil [1].

Concrete at the formwork

Minimum cubic compressive strength	R_{cmin}	15	MPa
Minimum cylindrical compressive strength	f_{cmin}	12	MPa
Partial safety factor for concrete	γ_c	1,5	-
Coefficient that takes into account long-term effects	α_{cc}	0,85	-
Mean value of cylindrical compressive strength	f_{cm}	20	MPa
Average value of axial tensile strength of concrete	f_{ctm}	1,61	MPa
Characteristic value of axial tensile strength (5% fractile)	$f_{ctk;0,05}$	1,1	MPa
Characteristic value of axial tensile strength (95% fractile)	$f_{ctk;0,95}$	2	MPa
Secant modulus of elasticity of concrete	E_{cm}	27267	MPa
Contraction strain in concrete at tension f_c	ε_{cl}	0,0020	-
Ultimate contraction strain in concrete	ε_{cu}	0,0035	-

Design tensile strength of concrete	f_{cd}	7,56	MPa
Design tensile strength of concrete	f_{ctd}	0,73	MPa
Permissible stress in concrete in the characteristic combination	$\sigma_{c,carat.}$	7,2	MPa
Allowable stress in concrete in quasi-permanent combination	$\sigma_{c,q.p.}$	5,4	MPa

This table details the characteristics of the high-precision steel molds used in the casting process, which are the fundamental enablers of the Multiblock system's functionality. The technical data confirms that the facility utilizes industrial-grade steel formwork, ensuring strict dimensional accuracy for every element produced. Unlike makeshift or flexible molds, these rigid steel structures guarantee that critical interlocking interface, specifically the male pyramidal studs on top and female recesses on the bottom are cast with perfect consistency. This standardization is vital for the product's application: it ensures that blocks manufactured at different times will still fit together seamlessly on-site, allowing for stable, mortar-free assembly. Crucially, this table validates the recovery of waste concrete is managed with the same industrial rigor and precision as the company's primary manufacturing lines [1].

Common characteristics of concrete

Specific weight	γ_{cls}	2430
Minimum cement content	C_c	360
Max water-cement ratio	a/c	0,45
Permissible exposure classes (ref.: UNI EN 206 and UNI EN 13369)	XC0-1-2-3-4; XD1-3; XS1-3; XF1; XA1	

B450C-B450A steel

- Characteristic breakdown voltage $f_{t\ nom}$ 540 N/mm^2
- Characteristic yield stress $f_{y\ nom}$ 450 N/mm^2
- Partial safety factor of steel γ_s=1,15
- Maximum steel stress in s.l.u. condition f_{yd}=4500/1.15=3913daN/cm^2

- Calculated adhesion resistance

$f_{bd}=f_{bk}/\gamma_c=2,25\eta\ f_{ctk}/\gamma_c=2,25*1*24,45/1,5=36,67$ daN/cm^2

- Maximum steel stress in service condition

$\sigma_s<0,80f_{yk}=3600$ daN/cm^2

- Elastic modulus E=200.000 N/mm^3

And complies with the requirements indicated in table 11.3.Ib of the ministerial decree of 17/01/2018 [1].

Tab.11.3.Ib

Characteristics		Requirements	Fractile (%)
Yield strength characteristic	f_{yk}	$\geq f_{y\ nom}$	5.0
Characteristic voltage at maximum load	f_{tk}	$\geq f_{t\ nom}$	5.0
$(f_t/f_y)_k$		$\geq 1,15$	10.0
		$<1,35$	10.0
$(f_y/f_{y\ nom})_k$		$\leq 1,25$	10.0
Lengthening	$(A_{gt})_k$	$\geq 7,5\%$	
Mandrel diameter for 90° bending tests and subsequent straightening without cliques	$\Phi<12$mm	4Φ	
For	$12\leq\Phi\leq 16$mm	5Φ	
For	$16<\Phi\leq 25$mm	8Φ	
For	$25<\Phi\leq 40$mm	10Φ	

Tab. 11.3.Ic

Characteristics		Requirements	Fractile (%)
Yield strength characteristic	f_{yk}	$\geq f_{y\ nom}$	5.0
Characteristic voltage at maximum load	f_{tk}	$\geq f_{t\ nom}$	5.0
$(f_t/f_y)_k$		≥1,05	10.0
$(f_y/f_{y\ nom})_k$		≤1,25	10.0
Lengthening	$(A_{gt})_k$	≥2,5%	10.0
Mandrel diameter for 90° bending tests and subsequent straightening without cliques	for Φ<10mm	4Φ	

This table details the mechanical requirements for the steel reinforcement used in the Multiblock elements. The parameter listed specially the Yield Strength and Tensile Strength confirm that the reinforcement meets the rigorous standards for structural steel. This ensure that the blocks possess the necessary tensile capacity to resist handling stresses and internal forces [1].

A critical safety indicator is Elongation at maximum force A_{gt}, which is required to be ≥2,5%. Combined with the tensile-to-yield ratio $(f_y/f_{y\ nom})_k \geq 1{,}05$, these metrics guarantee that the steel is sufficiently shapable. This means that in the event of overload, the reinforcement will deform plastically rather than snapping brittleness, providing a crucial safety margin. In the table we see "Fractile" values 5% to 10% for these properties. This indicates that the steel's performance is not random but statistically guaranteed. The strict limits on the yield ratio $(f_y/f_{y\ nom})_k \leq 1{,}25$ further ensure that the material behaves predictably under load [1].

This data proves that the multiblock system is not merely a "concrete block" but a reinforced concrete structural element. The use of certified steel with defined ductility and strength properties allows these blocks to be used safely in demanding engineering applications, such as high retaining walls, where structural integrity is paramount [1].

Multiblock verification calculations

The Multiblock element was created as a prefabricated component for the construction of gravity retaining walls for the containment of earth and loose material of any kind, greater than one meter in height. The convexities and concavities of two surfaces of Multiblock were specifically designed to allow the connection between overlapping blocks, which can be of the same type (MB16 – MB16 or MB08 – MB08 – figure.14), but also of different types (MB16 – MB08 – figure.15); from the same family, or, more generally, Multiblock blocks from different series (figure 16 and 17) [1].

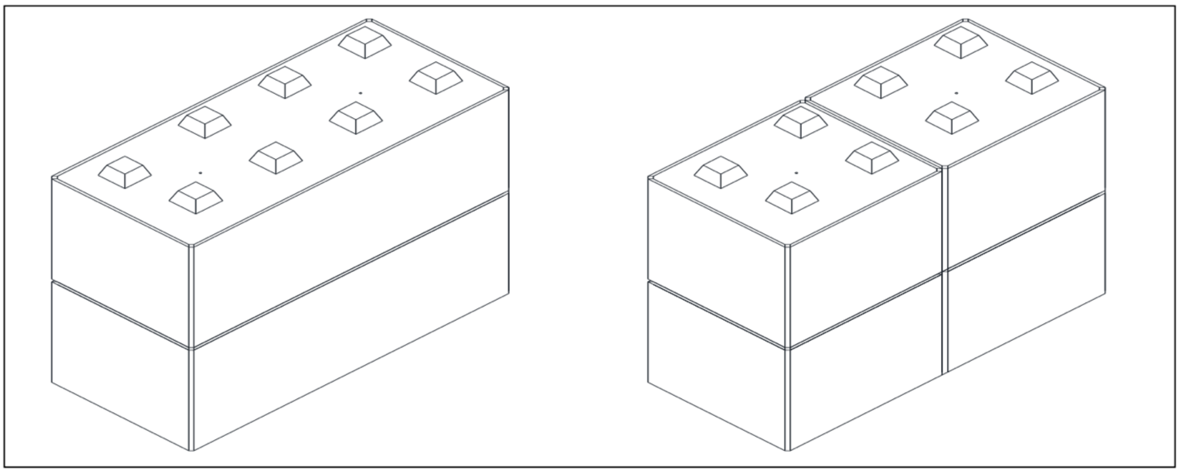

Figure 26

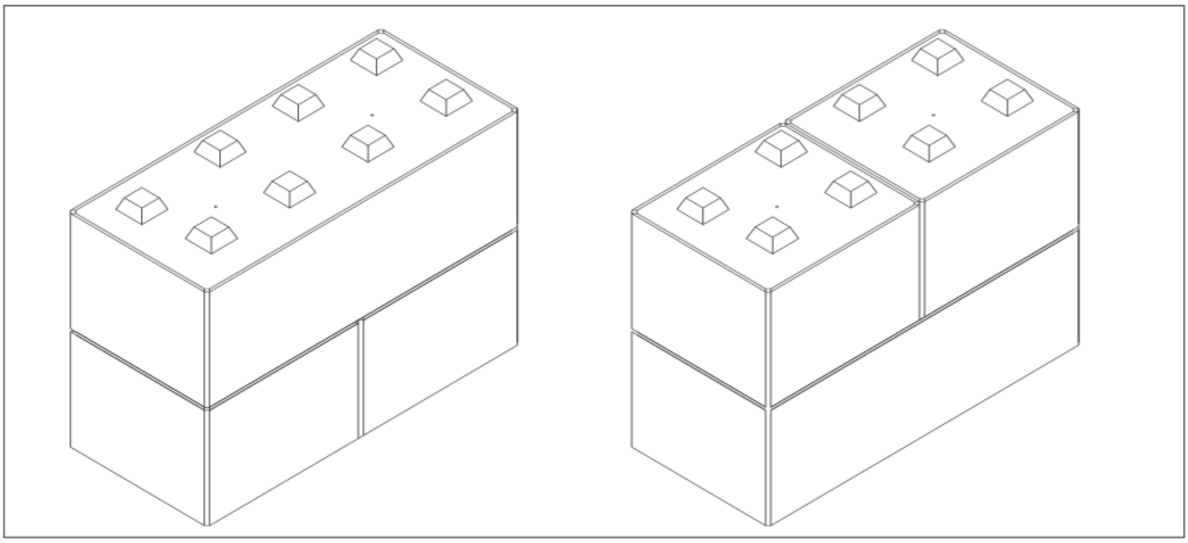

Figure 27

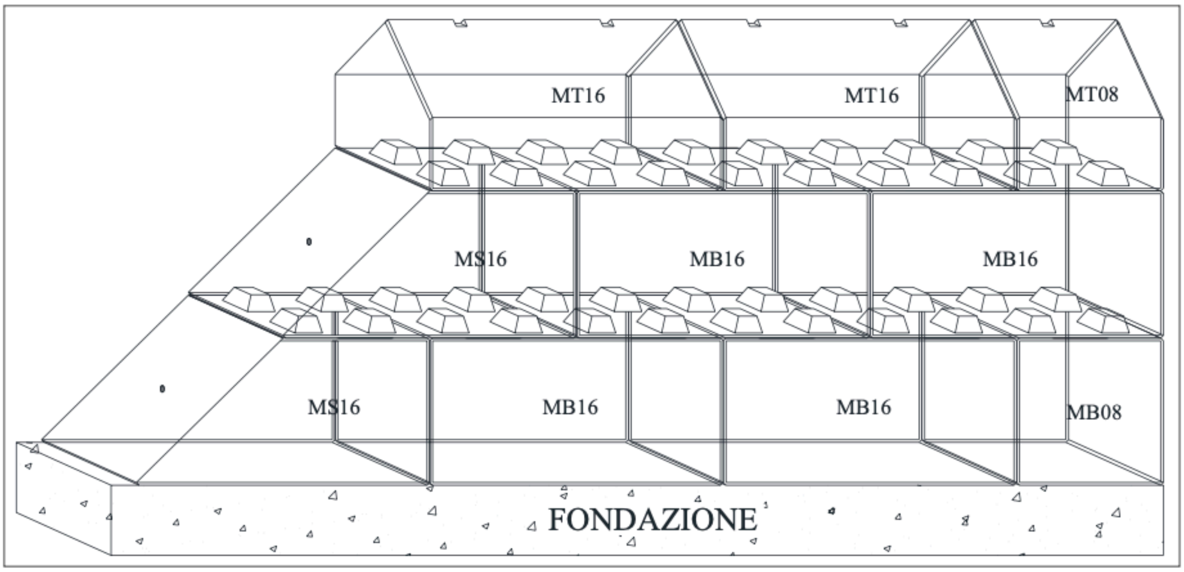

Figure 28

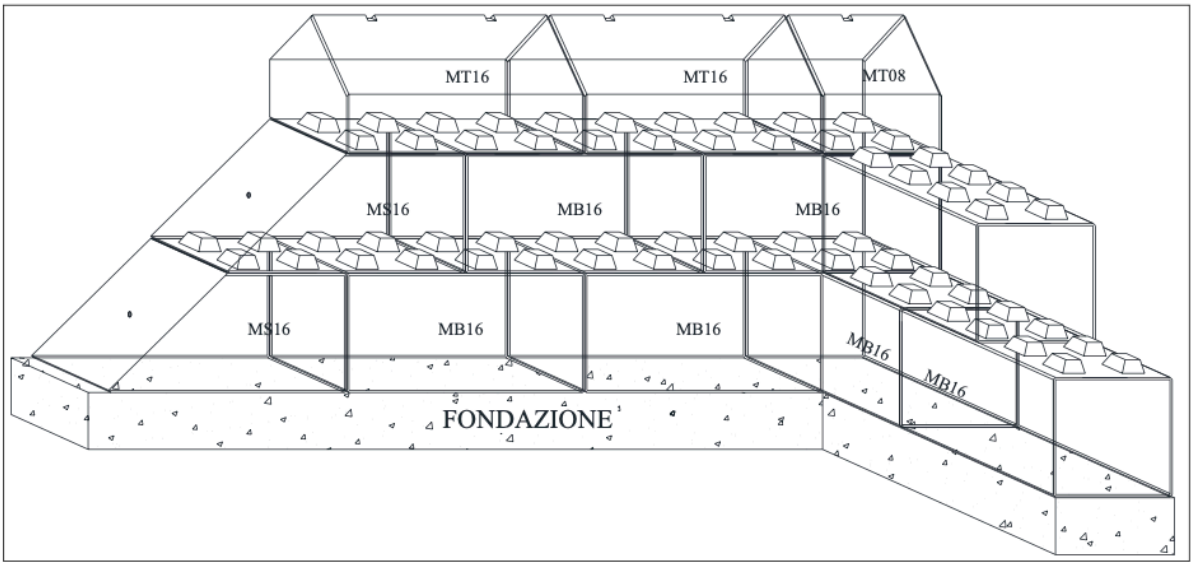

Figure 29

The construction phases of a Multiblock element from the production plant to the off-site construction site are:

1. Forming the reinforcement cage
2. Placement of the reinforcement cage inside the formwork, after applying release agent to its surfaces, and insertion of spacers
3. Pouring concrete

4. Removal of formwork
5. Transport to the storage yard
6. Storage (completion of concrete curing)
7. Transport to construction site
8. Storage on the construction site
9. Installation
10. Operational phase

During operation, the use of these elements for the construction of gravity retaining walls must always be justified by a design calculation that guarantees the correct stability of the wall itself under the operating loads, thus providing for the calculation of foundations and connections (foundation-wall) adequate for the static and dynamic (horizontal) loads resulting from the calculation [1].

Truzzi S.p.A. declines all responsibility for improper use of Multiblock products.

Storage

Multiblock elements (MB08, MB16, MT08, MT16, MS16) must be stored in stacks composed of non-homogeneous elements, to ensure stability, and in any case with a maximum of 3 elements per stack along the vertical axis. Wooden planks of adequate height must always be placed between the elements to prevent direct contact between the elements. Under no circumstances should the blocks be stored using the interlocking system of blocks themselves, to prevent accidental impacts during handling that could damage the wedges and render them unusable [1].

When storing, especially when stacking up to three elements high, it is important to always ensure the stack is vertical (even if it is temporary storage) and to ensure that the installation surface has the necessary load-bearing capacity to ensure stability. Below are some possible storage solutions [1].

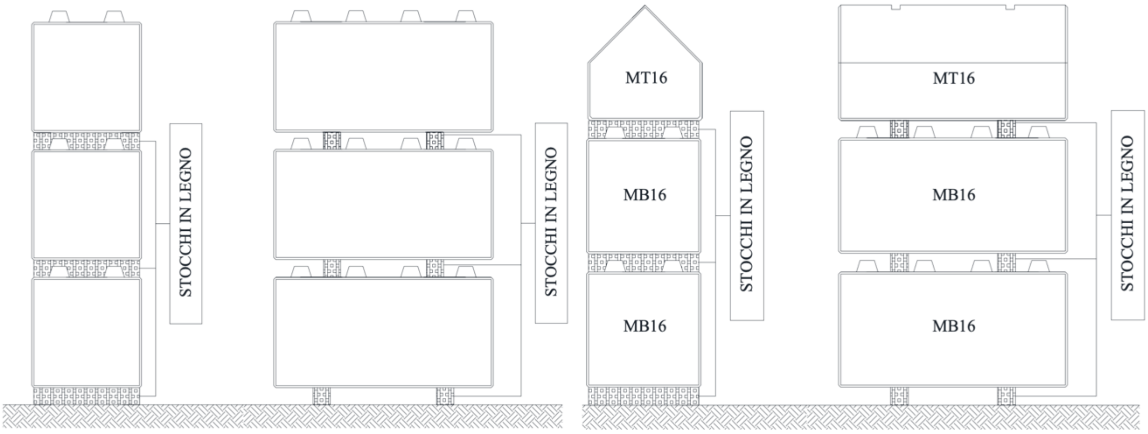

Figure 30

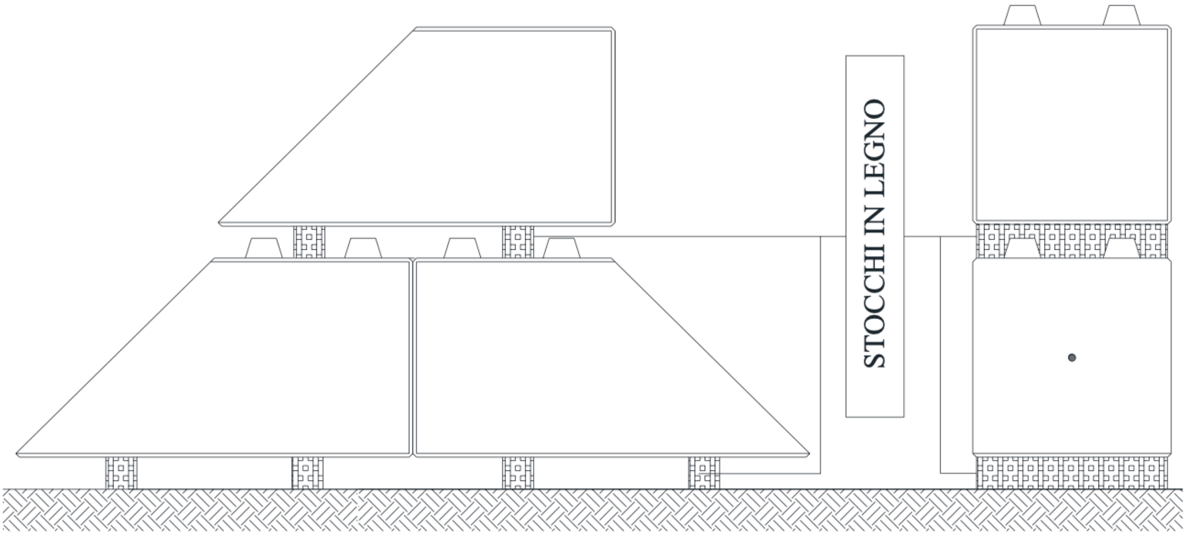

Figure 31

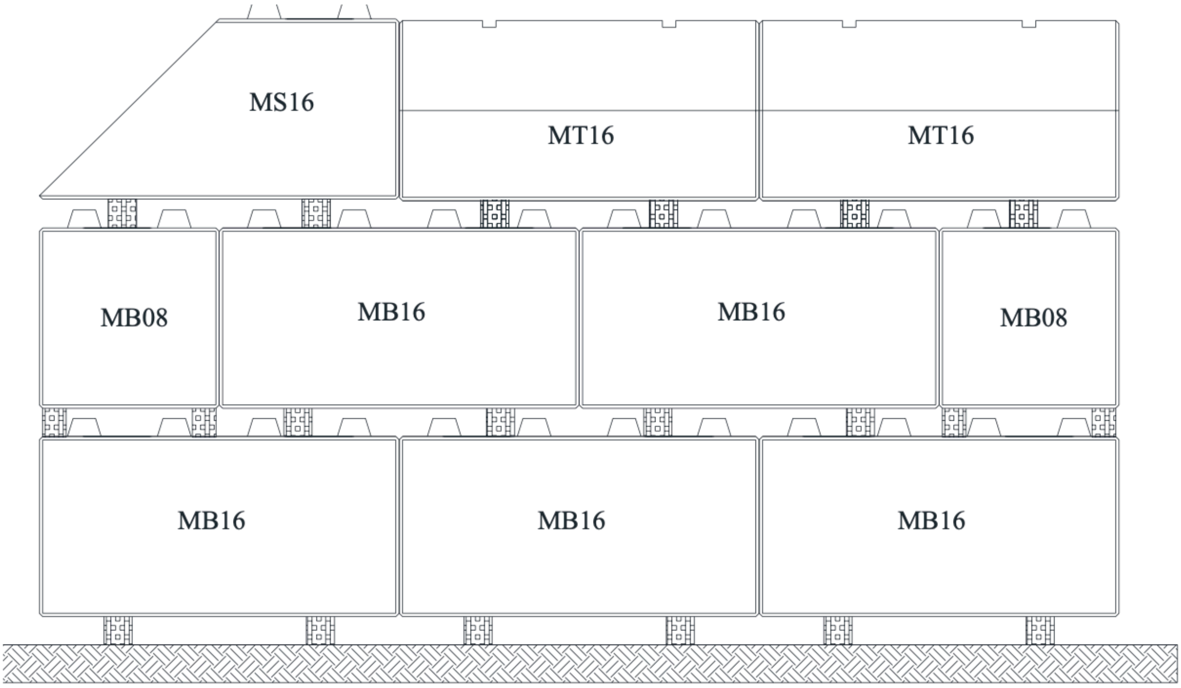

Figure 32

Handling

Each individual Multiblock element with a maximum length of 1.60 m must be lifted using a crane with two chains or ropes attached to the element's bushings; if the maximum length is 0.80 m, a single rope or chain is sufficient. Handling must be gradual, avoiding sudden changes in speed during both loading and unloading. For internal transport to construction sites, the elements must be placed on wooden stacks placed on a trailer towed by a tractor or similar vehicle [1].

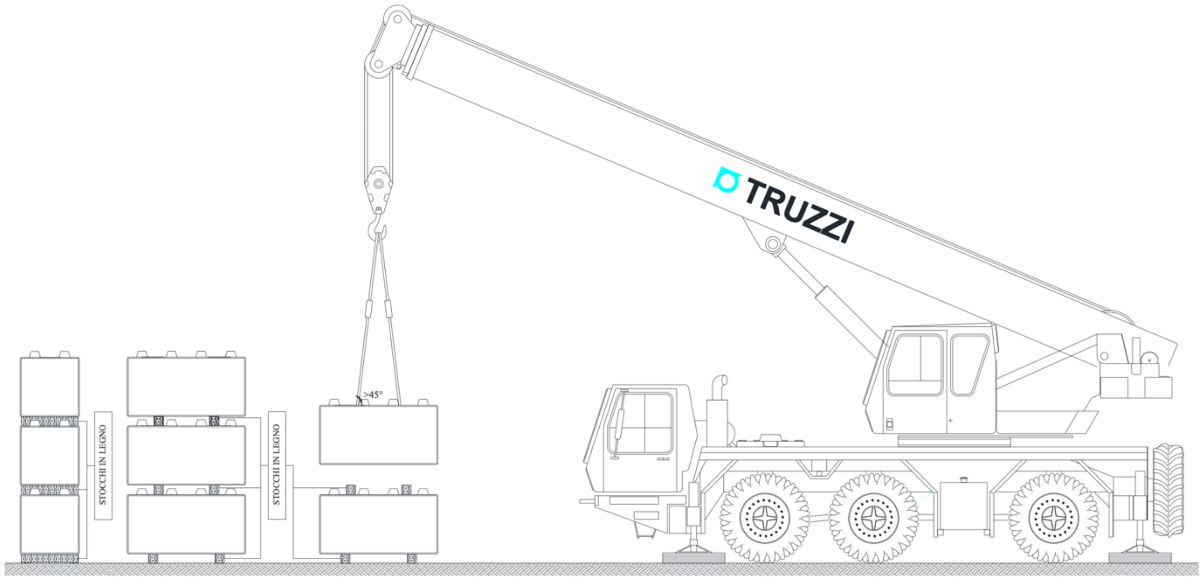

Figure 33

Installation

Thanks to the specific design of square-section truncated pyramid wedges, the Multiblock elements allow for a wide range of interlocking options between the elements of the different series (MB, MT, MS). To ensure the stability of the structure, the elements must be installed following specific structural calculations prepared and signed by a qualified technician accordance with the current legislative provisions [1].

The installation of the multiblock elements must be carried out according to the methods described above for handling, and with great precision during installation to ensure the coplanarity of the elements [1].

Summary table of elements

Element code	Geometric dimension				Weight(t) toll 5%	Exposure class	R_{ck} (Mpa)
	Length (cm)	Width (cm)	Height block (cm)	Height overall (cm)			
MB16	160	80	80	88	2,51	XC0-4; XD1-3; XS1-3;	50
MB08	80	80	80	88	1,26	XC0-4; XD1-3; XS1-3;	50
MT16	160	80	40/80	88	1,88	XC0-4; XD1-3; XS1-3;	50

MT08	80	80	40/80	88	0,99	XF1; XA1	
MS16	160/80	80	0/80	88	1,88		

The most critical data point in this table is the compressive strength (Rck) of 50 MPa. This confirms that although the Multiblock is made from residual concrete, they retain the high-performance mechanical properties of the primary production beams and pillars. The weight specifications ranging from 1,26 to 2,51 tons per block, indicate significant mass. This high density is essential for their function as "gravity retaining walls" where the stability of the wall relies entirely on the weight of the individual blocks. The listed exposure classes (XC0-4, XD1-3, XS1-3, XF1, XA1) demonstrate exceptional durability. These blocks are certified to withstand aggressive environments, including chemical attach, freeze-thaw cycles, and saltwater exposure. This proves that the multiblock system is suitable for demanding industrial and infrastructure application [1].

The guideline for understanding the exposure class is listed below:

1. XA1 refers to Chemical Attack
2. XF1 (Freeze-Thaw)
3. XS1-3 (Saltwater/Seawater)
4. XD1-3 (De-icing Salts)

5.3 Industrial aggregate (DIMA 4-8)

Dima is industrial aggregate. It is a recycled mineral aggregate obtained from industrial byproducts. Specifically, it is carbon steel slag from an electric arc furnace (EAF-C). After appropriate treatment, which includes cooling, crushing, and magnetic separation, it is used as a high-performance aggregate. It is CE certified according to the harmonized standard EN 12620 and complies with the technical requirements for concrete production. The use of this industrial aggregate helps reduce the extraction of virgin raw materials and avoids landfilling of industrial waste. Its reuse supports the principle of the circular economy and significantly reduces the environmental impact of concrete [1].

In a simpler way, when concrete is made, normally we should go to nature (river and mountain) to obtain sand and aggregate. It will destruct nature, but when we use industrial aggregate (Dima) we are using recycling industrial and construction waste [1].

This material does exactly the same thing that natural sand does for us. It is like a concrete bulking agent but, with a remarkable difference, it has EPD license. It proves that carbon footprint is less than normal sand. We buy this and we substitute it with normal sand [1].

It shows us that the material which consider as waste, has processed and become clean and again it enters to the production cycle.

Using industrial aggregate result in less mining and less waste.

Why it matters for the circular economy:

By using Dima into our mix design, the company actively closes the material loop

- Virgin resources preservation: every ton of DIMA used is a ton of natural gravel that remains untouched
- Landfill diversion: this material prevents construction debris from occupying valuable landfill space [33]
- Carbon footprint: the EPD data confirms that the embodied carbon of this recycled aggregate is significantly lower than that of extracted aggregates. It reduces the overall Global Warming Potential (GWP) of our concrete products [34]

6. Discussion and conclusion

This study set out to evaluate the impact of introducing a strength-enhancing additive (Mapecube1) into two concrete mix designs traditionally used for the production of Coppelle and Pillars. The primary objective was to reduce the environmental footprint of concrete production—specifically, by lowering cement content—without compromising mechanical performance or structural integrity [1].

Experimental results confirmed that the modified concrete mixes, R50/25 for Coppelle and R5/25 for Pillars, not only maintained the compressive strength of the original mixes but in some cases significantly outperformed them. In particular, the R50/25 mix achieved a 26% increase in compressive strength at 28 days compared to the control mix. Similarly, the R5/25 mix showed excellent compressive strength, well above the design threshold of 50 Mpa [1].

From an environmental standpoint, both modified mixes demonstrated a reduction in greenhouse gas emissions per cubic meter of concrete. The emission savings—21,53 $kgCO_2eq/m^3$ for the Coppelle mix and 17,22 $kgCO_2eq/m^3$ for the Pillar mix—are largely attributed to the reduced cement content and the efficiency of the additive. The total annual CO_2eq saving across both product lines would have exceeded 92,59 Ton CO_2 eq had the modified mixes been implemented in 2024 [1].

Although the modified mixes led to a marginal increase in material costs (2.31% for R50/25 and 0.04% for R5/25), these are offset by substantial environmental benefits and improvements in long-term mechanical performance. The findings strongly support the adoption of performance-enhancing admixtures as a viable strategy for more sustainable and resilient concrete production in the construction industry [1].

The Comprehensive energy transition implemented at Truzzi S.pA. demonstrate that decarbonization is not merely an environmental obligation, but a strategic asset. By replacing fossil-fuel-based electricity with 428.4 kWp Photovoltaic System the facility has significantly lowered its Scope 2 emissions, achieving a high degree of energy independence. Furthermore, the bold decision to eliminate natural gas from the curing process has proven to be a masterstroke. The data confirms a 93% reduction in methane consumption during the critical winter months, directly translating into a net economic saving of over €69 thousand in a single year. This successful pivot from fossil fuels to renewable electrification proves that industrial efficiency and environmental stewardship can go hand in hand, creating a production model that is both greener and more profitable [1].

On the other hand, the transition to a direct recovery system represents a definitive shift from waste treatment to resource preservation. By eliminating the intermediate filtration step, Truzzi S.p.A. has successfully transformed a potential waste stream into a continues resource loop. This intervention yields a triple benefit: it eliminates the production industrial sludge

(Zero waste), reduces electricity consumption by decommissioning the filter press, and eliminates the indirect CO_2 emissions associated with waste transport. Ultimately this establishes a "Zero Liquid Discharge" process that is both environmentally resilient and operationally efficient.

Further, the multiblock system exemplifies the concept of "Upcycling" within an industrial setting. By intercepting fresh concrete residue before it becomes waste, Truzzi S.p.A. has successfully converted a disposal liability into a profitable asset. This initiative not only ensure zero material waste for the facility but also provides the construction market with a versatile, high-strength product that promotes dry assembly and reusability. Ultimately, the multiblock project proves that with smart design, even the inevitable by-products of production can be reintegrated into the value chain.

And at the end, DIMA marks a critical evolution in company's supply chain management. By substituting virgin raw materials with certified "End-of-Waste" aggregates, the company actively reduces the embodied carbon of its final products before production even begins. This strategy demonstrates that high structural quality and environmental responsibility are not mutually exclusive. Ultimately, DIMA 4-8 serves as the vital link that. Transforms the construction industry's waste problem into a raw material solution, effectively closing the loop at the very beginning of the value chain.

6.1 Future innovation: emerging niche technologies

While the strategies analyzed in this thesis focus on optimizing standard production, Truzzi S.pA. acknowledges the potential of integrating existing but underutilized technologies. These "niche" innovations, currently applied only in specialized high—end projects, represent the next logical step for mass industrial adoption:

1. Photovoltaic Concrete ("Smog-Eating "Surface) An immediate opportunity for innovation is the surface treatment of precast panels with Titanium Dioxide (TiO_2). This technology gives the concrete "active" properties. Through photocatalysis, the panel surfaces react with sunlight to decompose atmospheric pollutants (specially Nitrogen Oxides, NO_x) and prevent organic staining. Integrating this into facade elements would transform industrial buildings into active air purifiers, adding a "social sustainability" value beyond simple carbon reduction [35].

2. Textile Reinforced Concrete (TRC) currently the facility relies on traditional steel reinforcement which dictates a minimum concrete cover to prevent corrosion leading to heavier panels. Future development could explore Textile Reinforced Concrete, where non-corrosive carbon or glass fiber grids replace steel mesh. This technology allows for the production of ultra-thin, lightweight, and durable architectural skins. By

significantly reducing the volume of concrete and weight per element, TRC drastically lowers transportation emissions and raw material consumption [36].

3. Self-healing "Bio-concrete" maintenance and durability are critical for lifecycle assessment (LCA) of structures. An emerging solution involves incorporating specific bacteria or healing capsules into the mix design. In the event of micro-cracking, these agents are activated by moisture/air to produce limestone, effectively sealing the crack autonomously. While currently a premium solution, adopting this for critical infrastructure elements would extend service life and reduce long-term repair cost [37].

6.2 strategic insight from state-of-the-art research (Net-Zero 2024)

Inspired by findings presented at the 1st International Conference on Net-Zero Built Environment (Oslo, 2024). Truzzi S.p.A. identifies three advanced research avenues to further enhance its circularity and decarbonization roadmap:

1. Valorization of "Fine Fractions" as Cement Substitute Current recycling at the facility focuses on aggregate (DIMA) and water recovery. However, recent studies presented at the Net-Zero conference highlight the potential of the "Fine Fractions" (micro-particles 63µm found in washing sludge) to act not just as inert filter, but as a reactive supplementary cementitious material (SCM). Implementing this would allow Truzzi to turn its filtration into a partial cement replacement, effectively closing the loop on the most carbon-intensive component of concrete [38].

2. AI-Driven Compressive Strength Prediction while Truzzi currently relies on physical 28-days compression test for quality control, emerging research demonstrates the efficacy of Machine Learning (ML) algorithm in predicting geopolymer and concrete strength. By feeding production data (temperature, mix proportions, humidity) into ML model, the facility could predict structural performance in real-time. This "Digital Quality Control" would reduce waste from failed batches and optimize cement consumption with extreme precision , moving beyond traditional empirical methods [39].

3. Carbon-negative geopolymer binders (calcined and sludge) moving beyond lowcarbon cement, the next frontier is Geopolymer Concrete drived from industrial by-products. Research highlights the development of "one-part geopolymer binders" using calcined clay and carbide sludge. For a precast facility like Truzzi, adopting such binders for non-structural elements (like paving blocks or barriers) could result in products with a negative carbon footprint, actively sequestering more CO_2 than is emitted during their production [40].

Final closing statement

Ultimately, the transformation realized at Truzzi S.p.A. serves as a tangible blueprint for the wider precast industry. This thesis demonstrates that decarbonization is not an abstract environmental ideal, but a pragmatic operational strategy that drives efficiency, reduces costs, and ensures market resilience. By successfully bridging the gap between current limitations and future innovations, this research confirms that the path to Net Zero is achievable. It proves that with the right integration of technology and vision, the "grey" legacy of concrete can be effectively transformed into a green foundation for the future.

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