Is Brussels WTC glazing a sustainable building material option for a tomato greenhouse project in Brussels?

Comparative LCA of different reuse scenarios

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submitted under the supervision of
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ABSTRACT

Green spaces and flat roof surfaces in Brussels carry an important potential of development for urban agriculture and appear as a promising solution to take a step towards food self-sufficiency. On the other hand, Brussels also accumulates an important building material stock and rejects a large quantity of construction and demolition waste. A major reconfiguration of World Trade Center’s (WTC) towers 1 and 2 is currently under way in the Brussels North district, casting aside about 14 000m² of identical bronze-tinted double-glazed windows. Circular actors declared that no reuse option other than reusing them in urban greenhouses projects had been found. This Master’s thesis aims to verify whether reusing WTC glazing into a heated urban tomato greenhouse project is a more sustainable option than investing in a new horticultural glazing.

Knowing that the most important part of the environmental impacts of a heated tomato greenhouse is its use phase, can reusing materials make a difference in the outcome? We used Life Cycle Assessment (LCA) methodology to compare the environmental impacts of three glazing options applied to a prototype. The three scenarios chosen are: reusing the double glazing “as it is” (WTC double scenario), reusing only the clear glass pane of WTC glazing (WTC simple scenario), and using brand new horticultural glazing (professional scenario). We chose the functional unit “the thermal and luminous atmosphere for producing one ton of tomatoes in an 18,7m² glass greenhouse heated at a temperature of minimum 18°C all year long in Brussels climate”. It turns out that the tomato production under a WTC double glazing greenhouse has higher environmental impacts than the two other options. Indeed, it is more insulating but also causes a poor yield and requires a heavier structure. On the other hand, reusing the clear side of WTC glazing has a lower environmental impact than the professional glazing scenario.

Some improvement levers of our prototype efficiency suggest that a non-tinted double glazing might be more appropriate for a greenhouse project than WTC glazing. This leads us to question the absence of data concerning the state of Brussels glazing stock, that ends up in landfills, or in the best-case scenario to recycling. It could be reused instead, but a good knowledge of Brussel’s global situation is essential in order to make informed decisions that will make a difference in connecting different sectors and heading to a general transition towards circular and autonomous cities.

Keywords: Urban agriculture, circular economy, greenhouse, Life Cycle Assessment, sustainable design.
**LIST OF ABBREVIATIONS**

<table>
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<th>Description</th>
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<tr>
<td>BCR</td>
<td>Brussels Capital Region</td>
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<tr>
<td>BIA</td>
<td>Building Integrated Agriculture</td>
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<td>BIGH</td>
<td>Building Integrated Greenhouse</td>
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<td>CDW</td>
<td>Construction and Demolition Waste</td>
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<td>CE</td>
<td>Circular Economy</td>
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<td>EOL</td>
<td>End-of-life</td>
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<td>FSGH</td>
<td>Freestanding Greenhouse</td>
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<td>GH</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>LT</td>
<td>Light Transmittance</td>
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<td>PAR</td>
<td>Photosynthetically Active Radiation</td>
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<td>RTG</td>
<td>Rooftop Greenhouse</td>
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<td>UA</td>
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<td>WTC</td>
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1 INTRODUCTION

Environmental crisis has shown the limits of industrial linear consumption model and the need for societies to reconsider their entire production systems. Following the United Nations “2018 Revision of World Urbanization Prospects”, by 2050, about 68% of human population will be living in urban areas.[1] However, the goods we consume everyday have never come from so far away than now.

One of the main challenges of the post-carbon transition is to find solutions to make our cities more resource-efficient, autonomous and productive. On the other hand, construction and demolition waste represent the largest part of Brussels non-household waste. Among these, an important quantity of flat glass that often ends up in landfill. Could this glazing be reused locally in urban greenhouses projects? In this work, we will discuss this question by treating the case of Brussels World Trade Centre glazing.

In 2010, the Institute for Climate Economics published a study where they evaluated that global food consumption represents about 28% of the world’s CO₂ emissions.[2] In 2017, the carbon footprint of food consumption (production and transport) of an average Belgian family was estimated to 8 tons of CO₂ per year.[3] In the 2017 Weber Shandwick Report on Belgium’s dietary trends, it was estimated that an average Belgian family of four person requires 8 tons of CO₂ in transport for their food.[3] This represents a quarter of the environmental impact of Brussels households. To reduce this impact, relocating food production in our cities appears a solution for reaching urban resilience and autonomy.

1.1 RE-LOCATING FOOD PRODUCTION IN BCR

Currently, cities alimentary systems are still mainly relying on importations. This has the two main disadvantages of making them vulnerable and dependant to road transport. It is also estimated that Belgium consumption is 6,3 times higher than its production.[4] A study conducted in 2008 assessed to 2500 kilometres the distance travelled for one average Belgian meal.[5] In 2012, the Food and Agriculture Organization of the United Nations published a ranking of the countries’ food self-sufficiency rate. Belgium was the world’s second lowest self-sufficient country.[6] Meanwhile, the Belgian population keeps on growing, the country has lost 63% of its agricultural exploitations between 1980 and 2010. This represents about 41 farms closing each week.[7]

As intensive agriculture presents significant negative impacts on the environment, urban agriculture might appear as a social and sustainable solution towards a more balanced food production system. A rise of urban agriculture has been observed in Brussels.[8] The number of urban vegetable gardens in the capital has doubled between 2005 and 2015.[9]
In 2016, BCR has launched the Good Food regional strategy establishing the objective that, by 2035, “urban and peri-urban agriculture will produce 30% of the unprocessed fruit and vegetables consumed by Brussels residents”. A rise in citizen initiatives for reducing the distance between the producer and the customer has also been observed with the creation of projects such as GASAP, La Ruche qui dit oui, cooperative supermarkets or urban shared vegetable gardens.

In addition to responding to environmental issues, Urban Agriculture (UA) could also bring new jobs in the region. Indeed, according to study conducted by the “Centre d’études régionales bruxelloises” of FUSL (Facultés Universitaires Saint-Louis), open ground and rooftop urban agriculture could create up to 1400 jobs in Brussels Capital Region.

While the need of Brussels to reconnect to take a step towards food autonomy, its climate often appears as a major constraint to growing food in open air. Indeed, with an average temperature of 10.3°C, 132 days of rainfall and 1502 hours of sunshine a year, Belgian winter is particularly dark and cold. The months of November, December, January and February are critical with average maximal temperatures below 10°C and less than 100 hours of sunshine per month.

However, this doesn’t mean that the yield of the Belgian agricultural land is nil. Indeed, cabbage, apples, nuts, mushrooms, beets, potatoes, turnips, Jerusalem artichokes and squash can still be produced locally and outdoors. The variety is yet considerably reduced, and the addition of a greenhouse as an agricultural supplement allows to extend the growing season of some fruits and
vegetables, but to also locally grown products that are usually imported from abroad like tomatoes, cucumbers, etc... In addition to the greenhouse effect provided by sun rays passing through the covering turned into heat energy, greenhouses also provide shelter for the plants, keeping them protected from pests, undesirable insects and wind [12].

Despite the unfavourable weather, Belgium is a particularly important tomato producer. Indeed, statistics estimate to 256 000 tons the tomato production in Belgium in 2017 [14]. In 2018, about 220 000 tons were exported abroad, like to Germany, the United Kingdom or the Netherlands. Globally, tomatoes represent about 34% of Belgian vegetable exportations [15].

1.2 GREENHOUSES IN THE CITY

Greenhouses are architectural elements that exist since the Antiquity, using empirical knowledge of sun energy for growing and conserving fruits and vegetables. [16] Their typologies have evolved for millennia: from roman mica sheets covering a hole in the ground to innovant aquaponics systems, greenhouses remain a solution for growing fruits and vegetables and reach food self-sufficiency all year long in northern countries.

1.2.1 History

As architectural elements, greenhouses are part of horticultural processes that can also become part of the city. Greenhouse effect is an ancient empiric knowledge, used since the Antiquity to protect vegetables and fruits from the cold at night in holes covered with translucent “mica” sheets.

In the 19th century, due to the industrial revolution and great technical progresses in construction field, greenhouses get integrated to buildings in big European cities like London, Paris and Brussels. Their agricultural and living space functions split up. They appear under derived typologies like jardins d’hiver (winter gardens), verandas, rooftops gardens, bow-windows... Due to the delocalization of food production, its living space function mostly remains in city while productive greenhouses are displaced to the countryside. [16]

The interest for urban agriculture momentarily rises during World War II in the United Kingdom and in the United States with the emergence of “Victory Gardens” and the “Dig for Victory” movement, encouraging urban people to use parks and gardens surfaces to grow their own food.

The interest in food self-sufficiency rose again at the end of 20th century facing the climate crisis. [16] During the 1960’s and 1970’s, the fantasy of some architects has been to reach food and heating self-sufficiency by integrating productive solar greenhouses directly to their living space. Many experiments on solar architecture have proven the efficiency of Building Integrated Greenhouses
(BIGH) as a passive way of heating a house. However, experimental models like Earthships have proven the necessity of keeping the food productivity function of a greenhouse out of the living space, for health and comfort reasons. [16]

A contemporary illustration of this separation between the living space and its food production system could be the “Cité Boréale” project by TETRARC Architects in Nantes. In this co-housing project, the whole south façade is composed of a double skin of *jardins d'hiver*, and the collective garden surface has been split in plots where each household has access to a smaller greenhouse for growing their own food.[17]

![Figure 2: Cité Boréale, project by TETRARC Architects in Nantes][18]

However, Building Integrated Agriculture (BIA) has not disappeared and is still the object of research on new forms of industrial symbiosis. Indeed, by keeping the living and greenhouse spaces separated but connected by mechanical systems, both can benefit from each other’s advantages without suffering from their disadvantages. In addition to benefitting from heat loss recovery, controlled ventilation systems can ensure heat of CO₂ transfer at the moment and in the quantity needed, warranting a win-win situation for both.[19]

For example, rooftop greenhouses (RTG) project on top of supermarkets already have experimented a heat exchange between the cold rooms and the RTG. Also, a European Interreg research project called GROOF is currently specifically focusing on CO₂ exchanges between offices buildings and rooftop greenhouses. By extracting stale air from the offices, it enriches the atmosphere in the greenhouse, stimulating plant growth. The use of rooftop answers to the fact ground harvesting areas can be scarce in urban context. [19]
In Brussels today, urban agriculture appears at the heart of sustainable development objectives. As historical object, urban greenhouses have never been more actual, they come as a way of moving towards food self-sufficiency.

However, greenhouses building materials present embodied energy that cannot be neglected. Knowing the pace of renewal of offices buildings in Brussels, the question of reusing their glazing appears as an interesting way of climbing up the Lansink ladder and optimize building material stock in the city. Yet, the choice of the glazing is a crucial factor for a greenhouse to be productive, since it influences significantly the temperature and the ability of the plants to perform photosynthesis.

1.3 **CONSTRUCTION & DEMOLITION WASTE IN BRUSSELS**

In 2016, the Brussels Capital Region (BCR) adopted the *Programme Régional en Economie Circulaire* (PREC) where the objective is to mobilize resources and minimize waste in the region by developing ambitious circular economy policies in the city. In this report, the construction industry is considered as a key-sector up for improvement. Indeed, in terms of economics, it concerns about 12 000 regional companies. In terms of environmental impacts, Brussels built heritage represents the most important material stock in the region (about 84% of the total mass). A study of Brussels urban metabolism showed that the building sector is particularly resource-intensive; it represents about 20% of entering material flows and 34% of non-household waste of the region.[20]

Historically, reusing building materials in new constructions was a common practice. Some companies were specialised in dismantling buildings and reselling materials.[21]. Today, BCR construction and demolition waste (CDW) represent about 650 000 tons per year.[22] Today, about 85% of this quantity is recycled, mostly by crushing concrete for backfilling, and another 1% is reused.[23]

One cause of this problem is the extremely rapid renewal of real estate park in Brussels, especially for offices buildings: as new offices buildings are being built, more existing offices spaces remain vacant.[24] Indeed, despite of the environmental impacts of the construction sector, many real estate companies keep on demolishing outdated but still perfectly viable buildings for reconstructing, instead of renovating them. This can be explained by the fact that demolition for reconstruction allows to optimize the living surface and answer the client’s demand and is, therefore, more economic than renovation.[22] This “obsolescence” of Brussels buildings on the market after 30 years is denounced by architects and urban planners.

Research projects are currently taking place for finding solutions to the problem of CDW and finding ways to connect different construction and urban design stakeholders. The objective is to
activate the circulation of these materials from deconstruction sites to local construction projects where they could be reused or revalorised into new functions without having to exit the city for recycling or landfill.

1.3.1 Brussels’ North District and WTC towers: a circular hotspot

The business area North District, currently undergoing major renewal with the renovation of WTC I and WTC II towers, was identified as a “hotspot” for building material resource. WTC I and WTC II towers were built in the 1970’s during a major modernisation operation of the city, by the architecture studio “Groupe Structure”. At this time, about 13 000 inhabitants had been expropriated from a residential neighbourhood to build a business district that would host all of Brussels trading activities (see Figure 32 in Appendices). These towers are witnesses of the flaws of Bruxellisation movement for modernizing Brussels by real estate companies that failed to respect architectural heritage and to carry a global vision for the city. Urban planners, inspired by New York City business district, called this project the “Manhattan Plan” (see Figure 33). [25]

Figure 3: Plan Manhattan project in North district [25]

Later, important companies preferred to flee the city centre for peri-urban areas like Zaventem, and these towers found themselves with large unoccupied offices surfaces. Today, a new renovation project called ZIN carried by Befimmo and 51N4E architects plans to re-affect most of the building with new functions, like co-working spaces, sports facilities, restaurants, housings and shops. The new spaces will be more flexible than the old WTC so the building can evolve in time. Their will is to create
as little waste as possible by innovating. The ZIN project will reuse part of the existing WTC structure, and reuse as much materials as possible on site, off site, or sent to recycling. In total, about 95% of the building materials and equipment of WTC towers will be revalorised by reuse or recycling.[26]

The regional ambition is to take advantage of its mutation to develop an hotspot of circular economy, knowing the numerous projects and the large quantity of future deconstructed materials.[27] This approach starts from the idea that hotspots are at the good scale, meso scale, to apply regional ambitions in Circular Economy (CE) without the limits of micro projects by creating a network of actors and infrastructure to enable local logistic.[27] The renovation of WTC I and II towers is the first phase of a deeper transformation of the whole North district.

1.3.1.1 Reusing the glazing of the facades of WTC towers
The two towers are now under deconstruction and contain a large quantity of materials whose 14 000 m² of double glazing available. So far, no concrete opportunity for reusing WTC glazing has been found. The challenge is now to find opportunities for reusing this glazing, that is insulating, but that is also bronze tinted. The glazing is not reused in the new ZIN project for unknown reason, but we assume that this glazing presents different a lower U-value than EPB-standard and an uncontemporary aesthetic (bronze tinted) or the specific dimensions.

In February 2019, circular actors working on the project announced that the only relevant reuse is by creating productive greenhouses. Following our latest contacts with Stephan Kampelmann from Brussels Chair in Circular Economy and Mathieu Depoorter from Ecores, WTC glazing will be dismantled and stored for one year waiting for responses to a call for reuse projects. Otherwise, it will be sent to recycling, which is usually the best-case scenario in renovation or deconstruction projects, since it is in most cases not up to passive standards anymore and needs to be replaced.
2 STATE OF THE ART

2.1 REUSE OF GLAZING IN CONSTRUCTION

Despite that the flat glass recycling is an extremely efficient process, only a small amount of deconstruction building windows ends up in recycling facilities. We found no data available for Brussels, but a study conducted in 2014 by the Confédération Construction Wallonne showed that most contractors evacuate flat glass with a mix of other non-dangerous waste, making it impossible to recycle. Some of the reasons are that evacuating it separately is too onerous, to a lack of alternative to their usual waste management system, to the risk it presents for the workers and a lack of storage. Yet, glass remains 100% recyclable and four collecting and recycling facilities exist in Belgium. Therefore, recycling remains an option that should be developed. [28]

However, reusing a glazing unit for extending its lifespan before sending it to recycling can be an interesting option, since flat glass has an extremely long lifespan and would avoid the production of a new unit. In the case where the glazing from a deconstruction site is recent and still air-tight and insulating, it can be directly reused in an architecture project. The openings in the walls will have to be dimensioned in function of the window, but the money saved can be consequent. For example, Superuse Studio architects designed a second-hand furniture store near Maastricht applying circular economy principles. They reused about 350 m² of glazing coming from a nearby housing building in the façade. [29]

Yet, most old windows are likely not to fill the thermal insulation standards for being reused in the façade of a building. For older windows, they can be repurposed in indoor design.[30] For example, Number Nine music studio in Gentbrugge reused a large double-glazed window they found on site for creating a partitioning between the kitchen and the corridor. [31]

Another way to repurpose old windows in housings could be to reuse them in a winter garden or in a veranda project. Indeed, since there is a risk that they don’t correspond to passive standards anymore to be reused in a building’s façade, they can still serve as a covering for a veranda or a winter garden, if they are thermally separated from the heated living space, to create buffer space between a house and the outside. We have not found much information on the subject except for some DIY tutorials on the Internet.

2.1.1 Reusing glazing into a greenhouse project in Belgium?

In 2017, Stephan Kampelmann with the association Osmos and RotorDC have already proven the feasibility of disassembling office tower glazing units from AXA tower near viaduct Hermann-Debroux
in Brussels. Stakeholders were interested in applying the principles of circular economy to the renovation project, conducted by Architectesassoc architecture studio. In total, among 730 glazing units have been dismantled by RotorDC, stock and transported for being reused in pilot projects of living greenhouses in the Netherlands, Poland and Belgium. [32, 33]

The same year, Osmos network also organised a workshop with a team of 12 students from ULB La Cambre-Horta Faculty of Architecture where they built an octagonal kiosque from reused double glazed windows from a primary school renovation in Mons.[34]

An article published in 2019 by A. Romnée et al., has already demonstrated the reduction of environmental impacts by reusing glazing units compared to a traditional greenhouse by using Life Cycle Assessment (LCA) methodology on their Tomato Chili greenhouse project.[35] In Brussels, DZEROSTUDIO architecture office already developed a greenhouse model made with reused glass panes, following functionality economy and circular design principles. The model is sold as a service and is made with reused wood and glass panes and is completely modular and demountable. Since the ambition of the project was to develop an innovative example of circularity, they conducted an LCA comparing the environmental impacts of buildings materials used for a “15 years of use of an 8.5 squaremeter-greenhouse with transparent walls and roof, located in Brussels”. The focus has been set on comparing the environmental impacts of a professional greenhouse with an aluminium structure to Tomato Chili greenhouse, that is made of reused construction site wood and glazing coming from separated double panes windows. The quality of the glazing material for being reused from a building to a horticultural function and its influence on the productivity of the greenhouse has not been considered.

Finally, an urban design project by 1010 Architecture and Urbanism studio reuses an old professional Venlo greenhouse in Tour et Taxis. Called Farmhouse, this 100m² greenhouse was supposed to be a temporary installation for the Parkfarm biennale in Brussels. Today, it is still open and hosts social events and cultural activities. The greenhouse was supplied and built by Hogervorst-Tabben, a Dutch company specialized in the construction and demolition of professional greenhouses that offers a range of second hand greenhouses and horticultural material.[36]

### 2.2 Designing a Productive Tomato Greenhouse in Brussels

Designing a quality greenhouse means creating an atmosphere favourable to plant growth considering the crop’s needs, but also the local climate where it will be implemented. Conception choices will play the role of intermediaries between the outside conditions and the production of the greenhouse. In
In this part of the chapter, we will enumerate some of the design parameters that can have an influence on the yield.

Many interconnected factors play a role in the productivity of a greenhouse system. Among these: the strength and the direction of the wind, CO₂ concentration, orientation, snow load,[37] quality of the soil, the arrangement of the plants indoor, thermal inertia, ventilation system, extra-insulation,... Table 1 contains a non-exhaustive list of factors that can contribute to the productivity of a greenhouse and how they apply to tomato production in Brussels climate. The parameters are divided into three groups:

- **External Environmental parameters** are the parameters that characterize the climate
- **Internal Environmental parameters** represent the atmosphere required for plant growth
- **Built Environmental parameters** are what make the intermediary between the External and Internal parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
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<tbody>
<tr>
<td><strong>External Environ. parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Daily direct sunshine</td>
<td>Lux</td>
</tr>
<tr>
<td>Outside temperature</td>
<td>°C or K</td>
</tr>
<tr>
<td>Wind</td>
<td>m/s or km/h</td>
</tr>
<tr>
<td><strong>Internal Environ. Parameters</strong></td>
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<tr>
<td>Inside temperature</td>
<td>°C</td>
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<tr>
<td>Humidity</td>
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<tr>
<td>Intensity of light</td>
<td>Lux</td>
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<tr>
<td>Length of wave of light</td>
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<tr>
<td>CO₂ concentration</td>
<td>ppm</td>
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<tr>
<td><strong>Built Environ. Parameters</strong></td>
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<tr>
<td>Location</td>
<td></td>
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<tr>
<td>Orientation</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td></td>
</tr>
<tr>
<td>Covering materials: heat transfer</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Covering materials: light transmittance</td>
<td>%</td>
</tr>
<tr>
<td>Artificial lighting</td>
<td>Lux</td>
</tr>
<tr>
<td>Ventilation</td>
<td>1/volume</td>
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</table>
Greenhouse harvesting can be extremely complex and requires excellent knowledge on plants growth and local climate. Thus, in this work, we will insulate certain factors for plant growth as a methodological choice in order to make a comparison between different greenhouse scenarios rather than making prediction on their yield. This means that some of the following factors will not be considered further in this work but are displayed for informational purpose. The most important thing to remember is that all these factors are deeply interconnected and that, as a simplification focusing on the evaluation of the glazing, we do not aim to establish a precise model of all greenhouse energy and material flows.

2.2.1 External Environment Parameters – Climate

The choice of the site is important when designing a greenhouse. One must understand the local climate well and should be careful to sun exposure, outside temperature and wind protection.

2.2.1.1 Daily direct sunshine [unit: lux and W/m²]

Since the purpose of the greenhouse is to create greenhouse effect, its performance lies on its ability to transmit light and heat and maintaining it inside. Therefore, daily sunlight has a major influence on its productivity.

Average daylight received by the ground surface varies between 0 lux at night and 150 000 lux on a summer day. The minimal light intensity in a greenhouse should remain above 15 000 lux. This represents the average diffuse light from a covered sky. However, 25 000 lux increases plant growth.[38]

Light is not received equally on the globe: it depends on the latitude, the season and the local weather conditions. Therefore, the greenhouse should be conceived considering its location, using a local sun chart, and its local climate, using average weather data.
Brussels is located at a latitude of 51°N, which means that there is a big difference of sunshine between the winter and the summer.

At the winter solstice, the sun stays very low and sunrays form an angle of 26° with the horizontal at the sun’s highest point. The Institut Royal Météorologique (IRM) of Uccle meteorological records between 1981 and 2010 indicate an average of 8 hours of sunlight a day in December, and an average global sunshine on a horizontal of 469 W/m² per day.

At the summer solstice, sun is higher, and the days are longer. The sunrays make a 61° angle with the horizontal at noon. The daylight lasts up to 19 hours a day and the ground receives an average global sunshine on a horizontal surface of 5309 W/m² per day in June, which is 11 times higher than in December.

At the equinoxes, sunrays form a 39° angle with the horizontal and the daylight lasts 15 hours per day. The average global sunshine on a horizontal is respectively 2138 W/m² per day in March and 3250 W/m² per day in September. [40]
Table 1: Hourly global sunshine on horizontal surface recorded at the IRM of Uccle for the months of March, June, September and December.

![Global sunshine on horizontal surface in Brussels](chart1)

<table>
<thead>
<tr>
<th>Time</th>
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<th>June</th>
<th>September</th>
<th>December</th>
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<td>12:00</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>650</td>
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</tbody>
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2.2.1.2 Temperature [unit: °C or K]

The heat transfer of the greenhouse covering depends on the delta of temperature between the inside and the outside. Therefore, outside temperature is also a major factor to take into account to make an estimation of the temperature inside an unheated greenhouse or the heating demand of a heated greenhouse.

Following the IRM records between 1981 and 2010, the average temperature in Brussels

Table 2: Average hourly temperature recorded at the IRM of Uccle for the months of March, June, September and December

![Average temperature in Brussels](chart2)

<table>
<thead>
<tr>
<th>Time</th>
<th>March</th>
<th>June</th>
<th>September</th>
<th>December</th>
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<tr>
<td>00:00</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>12:00</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

2.2.1.3 Wind [unit: m/s or km/h]

Evaluating the strength of the wind is also important when evaluating a location for building a greenhouse. Indeed, if the wind on the site has a speed above 5 m/s (18 km/h), heat losses can double.
because of the convection compared to a greenhouse that uses wind protection. The most efficient ways of preventing those heat losses are to plant shrubs or bushes around the greenhouse to make a natural windshield without making too much shading, or to design a tapering shape in the direction where the wind comes from.[41]

In Brussels, prevailing winds blow from the South-East to an average registered speed of 3,8 m/s (13,7 km/h). Following the average data between 1981 and 2010 from the IRM, the wind would be blowing above 5 m/s for 1923 hours a year, which represents 22% of the time.

2.2.2 Internal Environment Parameters - Atmosphere in the GH
The atmosphere inside a greenhouse artificially reproduces a microclimate to provide the optimal growing conditions for plants. The results can be obtained by using natural or more artificial principles of construction. The plants are growing in an atmosphere that must be carefully regulated according to their needs. It must match their optimum growth temperature as well as providing them the essential elements they need for performing photosynthesis: light, carbon dioxide and water.

2.2.2.1 Temperature [unit: °C or K]
Greenhouses can go from being a non-heated shelter protecting plants against wind and excessive rain to reproducing tropical climate conditions for growing exotic fruits. In any case, its conception choices have a major influence on its thermal performance. One general rule is that the difference between day and night should never exceed 10°C. Then different types of climates can be recreated in a greenhouse.

2.2.2.1.1 Warm greenhouses
This type of greenhouse functions with a minimal temperature of 20°C and is mostly used by professionals since they require very high heating energy, so their yield is optimal. From an energy point of view, it can be advantageous to reduce the surface of glazing and add some artificial lighting.[38] The humidity and ventilation must also be strictly controlled. Vegetables that require such temperatures includes cucumbers (18-29°C), eggplants (18-27°C) and tomatoes (16-27°C).[41]

2.2.2.1.2 Tempered greenhouses
This type of greenhouse is usually heated to a minimal nocturnal temperature of 15°C but can go down to a temperature of 7 or 8°C during wintertime to keep plants in reserve until spring.[38] Its crop varies in function of the seasons and almost every plant, excepted tropical and high-altitude varieties, can be grown in a tempered greenhouse. For example, tomatoes (16-27°C, seedling in July) or squash (13-23°C, seedling in May) can be grown during the warmer season, while spinach (4-10°C, seedling in
August or February) or lettuces (7-16°C, seedling in August or September) can be planted in the intermediate seasons.[41]

2.2.2.1.3 Fresh greenhouses
Fresh greenhouses appear as an ideal choice for an amateur gardener. They can be equipped with a “hot box” for seedling and minimum heating for keeping the greenhouse temperature above zero. Most vegetables and plants can grow normally but will not bloom or produce any fruits without an extra heating input outside of the warm season.[38]

2.2.2.1.4 Cold greenhouses
Cold greenhouses do not include any form of heating system. In Northern latitudes, only the most robust plants will survive the winter, but, when equipped with a “hot box”, cold greenhouses can still be an adequate tool for improving the crop yield of a garden during the warmer season, when sunlight is more abundant and temperatures milder.[38]

2.2.2.2 Humidity [unit: %]
The degree of humidity of a greenhouse must be directly linked to its temperature. A colder greenhouse will need drier air than a tempered or a warmer greenhouse. Optimal relative humidity varies in function of the season, but it is considered that it should be around 60%. This represents about twice the optimum relative humidity of a living space.

Relative humidity can be lowered to 40% without presenting major problems in the production if it is watered sufficiently. In contrast, its rise to 70% can lead to the appearance of diseases in the crop. While uncontrolled watering should be avoided, an efficient ventilation system can also prevent an excessive moisture in the greenhouse.

With the change in the outside temperature at dawn and dusk, condensation drops can appear on the inside of the walls. A design with inclined roof can prevent these drops from falling on the plants and damaging them.[38]

2.2.2.3 Light [unit: lux & nm]
The amount of light penetrating in the greenhouse also has a major influence on plants growth. During the winter, it is common to use artificial lighting to extend the duration of the period when plants perform photosynthesis. Some plants need a precise ration of daylight and darkness per day, while others are indifferent to the duration of light exposure. Both intensity and spectrum have an influence on the yield.
2.2.3.1 Intensity
The need for intensity differs in function of the variety, but generally, a low amount of light slows down the growth and an excess direct light makes the leaves burn. The minimal intensity rate for plants growth is 15 000 lux. An increase to 25 000 lux will lead to a better and faster growth. However, no improvement is observed when the intensity passes 30 000 lux.[38]

For tomatoes, for example, studies have shown that the average weight of a fruit could increase from about 14 grams when grown with a light intensity of 10 000 lux, to 30 grams with 20 000 lux and 40 grams with 40 000 lux.[38] However, studies found out that, if light intensity can have an impact on the yield of a tomato greenhouse, it does not show any impact on the quality of the fruit. Indeed, a study published in Acta Horticulturae in 2012 showed that neither cultivar, light intensity nor truss-leaf ratio influenced the allocation of soluble solids to tomato fruits per m² ground.[42]

2.2.3.2 Photosynthetically Active Radiation (PAR)
If light intensity has an impact on tomato yield, plants do not assimilate the entire light spectrum. Indeed, they use a spectral region between 400 and 700 nanometres to perform photosynthesis, which corresponds approximatively to the one visible to the human eye.

Figure 5: PAR necessary for plant’s growth [43]

Below a wavelength of 400 nanometres, the ultraviolet light remains dangerous for the plants. Then chlorophyll absorbs better the blue and red solar radiations. Blue spectrum, from 400 to 500 nanometres wavelength, helps regulate plants growth rates. Yellow and green light, from 500 to 600 nanometres wavelength, are reflected, giving plants their green colour.[44] Finally, red spectrum, between 600 and 700 nanometres, stimulates overall growth.[45] That means that the response to the photoperiod (day and night) is increased and the performance of photosynthesis is maximized.[38]
It is commonly considered that a reduction of 1% in the light transmittance of a greenhouse glazing could lead to a reduction of 1% in its yield. Tomatoes are no exception to the rule, even though studies have shown that this 1% rule is not true for every plant. [46]

2.2.4 \textit{CO}_2 \textbf{concentration [unit: ppm]}

During the day, when performing photosynthesis, plants consume large quantities of \textit{CO}_2 in order to produce glucose, the organic matter, that is then transformed into tissues while releasing \textit{O}_2 during cellular respiration.

Historically, first primitive plants appeared in an atmosphere very rich in carbon dioxide and that could explain why they still can capture much more \textit{CO}_2 than it is available the atmosphere today. Therefore, adding an input of \textit{CO}_2 the greenhouse can lead to a significant increase in plants growth, improving their receptivity to sunlight and heat.[38] Studies have shown that raising the \textit{CO}_2 levels from 340 to 1000 ppm in greenhouses with the same level of PAR could increase net photosynthesis by 50%. Studies also showed than an increase in \textit{CO}_2 in a greenhouse could compensate a lack of sunlight, but this option is often due to economic reasons.[47]

A small \textit{CO}_2 shortage in a greenhouse can have stronger effects than \textit{CO}_2 enrichment. When the \textit{CO}_2 level drops from 340 to 200 ppm, the effect on the yield is equivalent the increase from 340 to 1300 ppm.[47] Let’s also note that every plant does not respond equally to \textit{CO}_2 levels.

This \textit{CO}_2 can be directly brought by the heating system, by co-generation or by adding a compost inside the GH. GROOF European research program is currently working on the development of RTG on top of offices buildings with the objective of creating industrial symbiosis recollecting human \textit{CO}_2 emissions to the greenhouse for feeding the plants. Bruxelles Environnement marked their interest in this topic and recently launched a call for projects of RTG with the counselling of GROOF.[48]

2.2.3 \textbf{Built Environment Parameters}

2.2.3.1 \textit{Location}

The choice of a site for setting up an urban greenhouse is primordial. Like seen before, special care should be taken for sun exposure and wind protection. In cities, greenhouses can be installed either in open-ground in parks or private gardens, or integrated to buildings, usually on rooftops.

2.2.3.1.1 In open ground

Freestanding greenhouses are the most commonly used in commercial food production system.[49] The most common shapes are single or multiple connected gables or tunnels. They can be installed on any flat surface that has enough sun exposure and not too much wind.
The region of Brussels-Capital still owns some agricultural lands in Anderlecht, but urban gardens are also starting to sprout in many places in the city. Bruxelles Environnement estimated the surface of green public space to 2779 hectares, which represents about 18% of the surface of the city.[51]

Recently, following the GoodFood objectives to rise to 30% the amount of fruits and vegetables consumed in Brussels produced in the BCR and its hinterland, Terre-en-vue ASBL assessed surfaces available for professional urban farming in open ground in Brussels. It follows that 480 ha would potentially be mobilizable for growing food in the region.[52] Assessing agrarian to all this available space could allow to feed about 12% of Brussels population.

In addition to that, Brussels remains a city where private gardens represent the largest part in total green spaces. Following a study conducted in 1999 and recited by the IBGE in 2007, about 32% of BCR surface are green spaces. It was also estimated that about 30 to 40% to Brussels households have access to a private garden.[53]

In 2017, a FSGH project called “Tomato Chili” was launched by DZEROSTUDIO architects, in partnership with other companies from Greenbizz in Brussels.[54] They designed their greenhouse following the principles of circular economy and economy of functionality. The greenhouse is built with construction waste (wood and glazing) and is entirely modulable and dismantlable.

2.2.3.1.2 Rooftop Greenhouses

While free standing greenhouses are traditionally set up in open-ground, dense urban context often leads to using flat rooftops for urban food production. Rooftops greenhouses (RTG) have the advantage of benefitting from maximal sun exposure and from heat losses from the building for reducing the heating demand.

For example, a 350m² experimental vegetable garden was created by the ASBL “Le début des haricots” in 2012 on the rooftop terrace of the KBR in Brussels city centre. In addition to a sufficiently robust structure, the water evacuation of the terrace, the sun exposure and the easy access by elevator
made it an ideal location for hosting harvesting activities. Most of the food production process happens in open air, but a light geodome greenhouse made of wood and plastic film has been built for seedling. The garden collects the organic waste from the KBR and sells fresh vegetables to its cafeteria, but no interaction exists between the building and the greenhouse, the roof is only a location for the greenhouse and the garden. [41]

2.2.3.1.3 Building Integrated Greenhouses

The approach of building integrated greenhouse (BIGH) goes further into improving the metabolism of a building: the building and the greenhouse are designed as a whole and can exchange heat, CO₂ and water flows. In terms of circularity, the greenhouse recovers waste from the building to valorise it into food production.

![Diagram of greenhouse conversion process]

Figure 7: Potential benefits of integrating a greenhouse to a building [55]

A study conducted in 2014 by Bruxelles Environnement estimated that about 5 000 000 m² of flat roof surface would potentially be available for BIGH in Brussels[55]. This study identified a total of 4377 industrial, public and offices buildings with flat roofs that could be used for UA and developed five BIGH scenarios of pilot projects applied to different typologies of buildings.

Indeed, Brussels housing sector rooftops do not seem like the most promising for UA. First, small scale residential flat roofs do not represent a large enough surface than to potentially turn them into productive gardens. Concerning new housing buildings, the BIGH should be included to the project at
the early design stage in order to benefit from the gains that can be created by that symbiosis and consider that element in the passive standard certification. The residential building typology that could benefit the most to the addition of a BIGH would be social housings, since they are under the jurisdiction of the BCR that could offer a management of the gardens, but also for the gathering effect of having a rooftop garden and the economic asset of food self-production and heat losses reduction. [56]

Industrial buildings offer larger surfaces for harvesting and important quantities of CO₂ and water to recover but are more isolated from the living areas of Brussels and often require their structure to be reinforced for hosting a rooftop farm. [56]

Public buildings offer a large variety of functions that can be complementary to urban farming. For example, the air quality in schools is often concerning. Integrating a greenhouse to a school building can allow to extract the CO₂ vitiated air from classroom for enriching the greenhouse atmosphere and returning O₂ to the building. This can also be applied to department stores, supermarkets, or offices buildings, like suggested in GROOF research project. [56]

Following Alice Berten in her master’s thesis at the Ecole Polytechnique of the Université Libre de Bruxelles in 2018, turning the flat roof surfaces of 173 buildings in the Brussels canal area could allow to provide up to 33% of Brussels demand in fresh fruits and vegetables. [56]

For example, the Foodmet project in the Abattoirs of Anderlecht is the only example of large-scale urban farm in Brussels, yet the largest urban aquaponics farm in Europe. With its 1800 m² surface, its greenhouse uses the permanent 500kw of heating energy from the cold rooms in the market to produce about 35 tons of fish and thousands of organic fruits and vegetables per year.[57]

2.2.3.2 **Orientation**

The location and the orientation of the greenhouse must be chosen in order to maximize sun exposure and minimize windage.

For FSGH, historically, horticulturists always oriented their greenhouses on the North-South axis for having a uniform sunlight all day long. However, research has shown that greenhouses oriented on the East-West axis could reach higher temperatures and light, especially in latitudes above 40°.[38]

For RTG, the same rules apply. They have the advantage of being in height so have less chances to be surrounded by obstacles to light, but they are also more exposed to wind.

For a BIGH leaning against a house, a South-East orientation can turn the greenhouse into a sun captor and passive heating system for the house, if it is well controlled by its inhabitants or by a computerized system.
2.2.3.3 Shape

Greenhouses can take different shapes and use different materials. They should be conceived considering the prevailing winds. The inclination of the roof panes should also correspond to the height of the sun during wintertime.

The energy of the sunrays is better absorbed when they hit the glazing perpendicularly. It is commonly considered that the glass panes should have a slope calculated by adding 15° to the latitude where it is located. For example, Brussels being at a latitude of 51°, the ideal slope for the glazing of the greenhouse should be 51° + 15° = 66°.[38]

2.2.3.4 Covering material

Many types of materials can be used as coverage in greenhouse projects and each one presents advantages and disadvantages. It is important to know their characteristics and their technical specificities in order to provide the best design based on the input material. In this work, we will focus on two factors influencing the quality of the crop yield: heat transfer and light transmissivity.

At northern latitudes like Brussels (51°N), the heating demand of a greenhouse represents its major economic and environmental impact. Therefore, using insulating covering materials with a high LT is becoming more popular among growers. However, this increase in insulation and change in light transmittance can lead to several climatic factors in the greenhouse other than the temperature, like humidity or leaf temperature.[58]

2.2.3.4.1 Heat transfer

Glazing will play a major role in creating and maintaining the temperature needed by the plants. This will depend on many factors, but the ones we will take into account in this work, following a mathematical model built by Diego Hangartner from the University of Zurich in 2010 that considers solar heat gains and heat transfer with the outside.

First, the way glazing transforms the sun light radiation into heat will have a major influence on the functioning of the greenhouse. Solar heat gains of a greenhouse are determined by:

- The amount of sun energy received by the glazing,
- The glass fraction of the window, which is the ratio between glazed surface and the total surface of the window,
- The transmittivity of the glass for visible radiation and the reduction by shading or impurities on the window,
- And the energy transmittance of the glazing, which is the amount of useful heat that passes through the window.
Then, how it keeps the heat inside the greenhouse will influence the amount of artificial heating needed when the outside temperature is lower than the inside temperature. Heat transfer will depend on:

- the **U-value** of the glazing, which is the amount of W/m² transferred through the surface, based on the thickness and the conductivity of the material.

- The **delta of temperatures** between the inside and the outside of the window. The higher, the more important is the heat transfer.  

U-value for double glazing is much lower than for simple glazing.

**Table 3: U-value for different types of glazing[41]**

<table>
<thead>
<tr>
<th>Type of glazing</th>
<th>U-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horticultural glazing</td>
<td>5.7 W/m² K</td>
</tr>
<tr>
<td>Double glazing</td>
<td>Between 1.6 W/m² K and 3 W/m² K</td>
</tr>
</tbody>
</table>

**2.2.3.4.2 Light transmittance**

Light transmittance of the glazing will also have a major influence in providing the PAR that plants need for their growth. Like seen previously, it is considered that a decrease of 1% in LT leads to a reduction of 1% in the yield, so the choice of the glazing is critical for plants to be able to perform photosynthesis.[37]

In order to have an idea of the light transmittance of a glazing, fabricants can usually provide technical information about solar radiation of their products. Spectral curves for different types of glazing can be found online. For example, Saint-Gobain factory gives an illustration of spectral factors for some of their products:

*Figure 8: Light spectrum transmittance of Saint-Gobain PANILUX and PARSOL bronze glazing.[59]*

---

1 According to the formula for heat transfer
This way, we can link the light transmittance of the glazing to the PAR needed by plants, between 400 and 500 nanometres and 600 and 700 nanometres. In the case of bronze tinted glass, the decrease in light transmittance is about equal on the overall visible spectrum (400-700 nanometres).

Not all plants need the same amount of light and heat. In the case where the glazing is an imposed material, like in our repurposing project, knowing and understanding its proprieties can help choosing a crop adapted to those conditions.[60]

Table 2 : Light transmittance of different types of glazing [61]

<table>
<thead>
<tr>
<th>Type of glazing</th>
<th>LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horticultural glazing</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Double glazing</td>
<td>Between 35% and 80%</td>
</tr>
</tbody>
</table>

2.2.3.5 Artificial lighting

Artificial lighting can be used to compensate the lack of natural sunlight in the winter, the low transmittance of a covering, or just for increasing the yield of a greenhouse.

Traditionally, incandescent lights and neon lights were used to reproduce blue and red spectral region assimilated during photosynthesis. For the past decade, new LED lights appeared in professional horticulture for their ability to reproduce PAR needed for plant growth. By their contribution to growth, with a red spectrum wavelength, and morphogenis with a blue spectrum, they help grow sweet and tasteful fruits and vegetables.[62]

A study was published in the Journal of the American Society for Horticultural Science in 2002 comparing the effects of covering materials (D-Poly and glass) and supplemental lighting on a tomato greenhouse yield. It revealed that the marketable yield and the number of fruits per square meter in D-poly houses were higher than in glasshouses. This yield was increased by 15% for glasshouses and 23% in D-Poly greenhouses under supplemental lighting. [58]

2.2.3.6 Ventilation

Ventilation plays a major role in keeping a quality atmosphere in a greenhouse. First, it brings a constant amount of carbon dioxide and oxygen from the outside in order to keep the plants performing photosynthesis every day. Secondly, it extracts the excessive humidity and stale air from plants transpiration, for example at the end of the day when outside temperature starts decreasing and condensation appears on the internal walls of the greenhouse. Finally, it allows to regulate the temperature in case of overheating due to an excess of sun during the day.[38]

Ventilation can be either active (fans) or passive (windows). Forced ventilation should be used in case natural ventilation is not enough, or in colder climates for a better temperature control. Private
recreational greenhouses will usually only use natural, while most professional greenhouses will use a combination of both for maximal efficiency.[63]

In the winter, it is common to lower ventilation down to its minimum in order to limit the heat exchange with the outside. This can lead to CO₂ deprivation that can be fixed by using the heating system air emissions or placing a compost bin in the greenhouse for recollecting heat and CO₂.[38]

2.2.4 And many more...

In this chapter, we established a non-exhaustive list of parameters that could take part in the quality of a greenhouse. Of course, many more parameters that can influence the crop yield exist and should not be neglected when making a precise modulation of all thermal and material flows of an operational greenhouse. In our case, since we are focusing on the glazing and its influence on the heating demand and on the light intake in the GH, we will not extend on these points. This does not mean they have a minor influence on the quality of the greenhouse.

First, the harvesting techniques (in soil, in pots, hydroponics or aquaponics) will define the entire functioning of the greenhouse. Culture in soil or in pots will not require much maintenance but won’t produce large quantities of fruits and vegetables. A good organisation of the plants inside the greenhouse and a good care for the atmosphere in the greenhouse can still help a family towards food self-sufficiency. In contrast, hydroponics and aquaponics are more infrastructure and energy-intensive but will lead to a tremendous yield by making profit of every drop of water and fertilizer and every square meter. These systems are more adapted to professional horticulture and large-scale urban farming.

Then, technical components of a greenhouse were not detailed in this work but can also make a difference in its functioning. For example, choosing a heat recovery ventilation system instead of a classical system could allow to save some heating energy. Recovering rainwater to water the plants, placing a compost inside the greenhouse for CO₂ enrichment and natural heating, using bumble bees for pollination... many options exist for improving the use phase of a greenhouse.

Finally, bioclimatic design principles, like thermal inertial for heat storage, natural shading, thermal curtains for insulating the greenhouse at night... All this low-tech knowledge should not be ignored since it can make an important difference in the heating demand by maximizing the use of sun energy as a heating supply. When correctly designed and used, a solar greenhouse integrated to a house can even provide up to 80% of its yearly heating demand. Using a greenhouse as a solar captor in addition to its food production function can be extremely beneficial in some cases. We invite any reader that would be interested in building small-scale greenhouse to get informed on the topic and consult the literature on passive solar greenhouses and bioclimatic design.
The design of a greenhouse should ideally always be adapted to its context, to its use, and consider all the benefits that it can bring in order to make the most of it, with all its possibilities. The most important is to understand that these factors are numerous, deeply interconnected, and that each one could be subject to improvement.

### 2.3 Greenhouses Energy Systems

Greenhouses are vulnerable spaces that are extremely dependant on the outside conditions. They are extremely complex and dynamic systems and, like seen in the previous chapter the parameters influencing their functioning are numerous. Therefore, mathematical models can be very useful tools to find our way among design options.

Indeed, each variable can have a dynamic influence on the indoor environment of the greenhouse. This dynamic behaviour is a “combination of physical processes involving energy (radiation and heat) and mass transfer (water vapor fluxes and CO₂ concentration) taking place in the greenhouse and goes to the outside environment.” Many factors can have an influence on these processes, like local climate, atmosphere, the type of greenhouse, its controlling system, and the crop.[64]

Currently, many ways of modelling the functioning of a greenhouse exist. The more parameters considered by the model, the more precise the prediction of the greenhouse performances will be. They allow to draw conclusions on the shape of the greenhouse, its orientation, its use... A model can focus on one or another parameter. For example, Gupta and Chandra developed a model to define a set of design features for energy conservation for a greenhouse in India. It allowed them to come with the outcome that a gothic shaped greenhouse would require 2,6% to 4,2% less heating than a gable shaped greenhouse, or that the use of thermal curtains at night could allow to reduce by 70,8% its daily heating demand.[64]

In this work, we will focus on evaluating the performance of reused glazing. Therefore, a basic energy balance for estimating the heating demand including the glazing characteristics is an interesting way of comparing the different covering materials. A basic energy balance is based on the energy conservation law, that the amount of energy stored in the greenhouse equals the sum if internal and external heat gains less the heat losses. The quality of the glazing intervenes in the amount of solar heat gains and the amount of heat losses through the cover.
The mathematical model we used was based on this simple equation of energy conservation to estimate the heating demand of the greenhouse. It stated that the total energy demand equals the heat losses by air renewal and convection through the glazing less the solar heat and internal gains.

2.4 ENVIRONMENTAL IMPACTS OF TOMATO PRODUCTION

Statistics show that tomato production in Belgium has risen by 13% in 10 years. While it was approximately 223,000 tons in 2007, and 256,000 tons in 2017. This could sound like good news, since local production means less travelled distance and fresher products.

However, the environmental impacts of greenhouse harvesting have been denounced by environment protection organizations lately. Indeed, heated greenhouses can consume high quantities of energy for maintaining their productivity conditions. One could question the necessity of heating a completely glazed structure to a temperature of 18°C day and night during a dark and cold winter. In France, petitions have been signed to remove “organic” labels on products of heated greenhouses.

In Belgium, studies estimated that the carbon footprint of a kilogram of tomatoes produced locally in a heated greenhouse was about four times higher than a kilogram of tomatoes imported from Spain. Abroad, research is also unanimous on the subject.

An average heated greenhouse requires 1400MJ/m² while a non-heated greenhouse only requires 220MJ/m². If we consider a tomato crop yield of 50kg/m², this means that tomatoes produced in heated greenhouses require 28,000 MJ/ton while seasonal tomatoes produced in non-heated greenhouses only require 4400MJ/ton.
In the Netherlands, “Milieu Centraal” organization conducted a study on the environmental impacts of food production. They demonstrated that the energy demand (80MJ/kg) for heated greenhouse harvested fruits and vegetables was equal to those same products transported by plane on 4000km to 8000km.[66]

An Austrian study used the LCA methodology for assessing the impacts of the supply chain of tomatoes in an Austrian supermarket.[67] Using SimaPro software, they assessed the environmental impacts for one kilogram of ripe and healthy fruit, from the seed to the fruit. It appeared that tomatoes imported from Spain or Italy had a two times lower impact than Austrian tomatoes produced in energy-intensive greenhouses. However, the environmental impacts of Austrian seasonal tomatoes grown in less-intensive processes were 3.7 to 4.7 times lower than imported tomatoes.[68]

This conclusion is also shared in the UK by the Food Miles report on differences in food production systems: « The impact of food transport can be offset to some extent if food imported to an area has been produced more sustainably than the food available locally. For example, a case study showed that it can be more sustainable – at least in energy efficiency terms – to import tomatoes from Spain than to produce them in heated greenhouses in the UK outside the summer months. »[69]

In conclusion, buying local food does not always mean making a sustainable choice due to the extremely energy-intensive use phase of a heated greenhouse.

### 2.5 Reducing the Environmental Impacts of a Greenhouse

Like seen previously, heated greenhouses present high environmental impacts, mostly from their use phase. Here is a non-exhaustive list of the numerous ways of interfering in different life phases of the greenhouse:

*Table 4: Non-exhaustive list of ways to reduce the environmental impacts of a greenhouse*

| Construction phase | • Sustainable choice for building materials (reused, local)  
|                    | • Material-efficient design (gothic rather than gable)  
| Use phase          | • Technical improvements (CO₂ enrichment, artificial lighting, aquaponics or hydroponics systems)  
|                    | • Bioclimatic principles for heating control (building-integrated, orientate, insulate, inertia, shade…) increasing solar heat gains, adapting the crop to the season, or mechanical principles (heat exchanger ventilation)  


In this work, we will focus on improving the construction phase and the use phase by applying reused glazing and all its characteristics to a greenhouse. Interfering on this design parameter will have effects on both the construction and the use phase of the greenhouse:

By changing the covering material, this brings a chance of reducing the environmental of the construction phase, by extending the life of an old glazing avoiding the production and transport of a new one. It also brings a chance of reducing the heating demand of the greenhouse since the old building glazing is more insulating than a professional one.

The objective of our work is to find our way among these different parameters in order to determine whether reusing WTC glazing is a more sustainable option than investing in a new covering material (see options in Table 4).

### 2.6 Life Cycle Assessment as an Eco-Design Tool

Circular economy consists as a shift of paradigm from the actual linear production system towards a closed-loop system following a “trash as treasure” philosophy. Ideally, a cooperation of different stakeholders leads to establishing industrial symbiosis and lift pressure on natural resources. In this idea the end of one product’s life cycle can be an input material for a new product’s lifecycle.

Following the European Union Waste framework directive 2008/98/EC, the following hierarchy should apply waste management:

1. Prevention
2. Preparing for reuse
3. Recycling
4. Recovery
5. Disposal

<table>
<thead>
<tr>
<th>End-of-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Recyclability</td>
</tr>
<tr>
<td>• Design for disassembly...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Choosing a renewable source for heating (solar energy, wind energy, biomass, biogas, geothermal energy, co-generation, other sources of renewable energy)</td>
</tr>
<tr>
<td>• Using different cladding materials (more insulating, higher LT)</td>
</tr>
<tr>
<td>• Adapting our way of life: growing winter vegetables in non-heated greenhouses</td>
</tr>
</tbody>
</table>
However, reusing a material instead of producing a virgin one does not always lead to a reduction in the environmental impacts is not always the most environmentally friendly method. Circularity rises the questions of the processing needed for the preparation for reuse, but also of the quality of the use material. [70]

Life Cycle Assessment (LCA) is a methodology that can help inform these Circular Economy decisions to evaluate whether reusing a material instead of sending it directly to recycling and producing a virgin material is a sustainable option. Indeed, it is an ISO standardized scientific method of environmental impacts assessment by considering the whole life cycle of a product or a process. It allows to compare the environmental impacts in different categories for different production, as well as identifying the flaws in the life cycle of a product order to bring eco-improvements to the process.

![Figure 10: Life cycle of a product][61]

The ISO 14040 and 14044 norms describe LCA as a “technique for assessing the environmental aspects and potential impacts associated with a product”. It is conducted by applying this method divided in four main phases: [71]

- Goals and scope definition[72]
- Inventory analysis,
- Impacts assessment
- Interpretation.[73]

LCA can be used in many situations and for many purposes, as an introspective or retrospective evaluation of industrial processes, for evaluating new market products or public policies options... It is now well known in the scientific field as a powerful tool in eco-design processes and has started to extend to the construction field.

This work aims to compare different reuse scenarios of glazing in an urban tomato greenhouse in Brussels to find out whether they are a more sustainable option than investing in a new horticultural
gazing. The use phase of a GH is important but building materials also present embodied energy and can have an influence on the yield and not only the heating demand. Therefore, LCA brings a way of measuring progress in achieving circular economy. Since it allows to consider more variables than a mathematical model or an inventory of building materials, we can really determine whether reusing glazing makes sense in environmental terms in the case of reusing WTC glazing in a greenhouse.

However, there is currently no consensus on how to allocate the environmental benefits of reused products in the Life Cycle Inventory. There is no “true” answer for choosing an allocation system, but choices always must be motivated and explained.[74]

In the literature, we would information about the ways to consider recycled content in a process [75]:

- **Cut-off approach**: In this case, no credit is given to the environmental impacts of the recycled or reused content.

- **Avoided burdens approach**: Reused or recycled content is assigned an the upstream production in the new process and the burden avoided by the production of a new material is deducted.

- **Value-corrected substitution**: This method addresses the downcycling issue by considering a corrected value of the environmental impacts based on the price of the recycled compared to the virgin material. For example, an LCA conducted by researchers at the University of Natural Resources and Life Sciences of Vienna compared the environmental impacts of new and reused washing machines used an allocation system for reused content based on the market value of reused products compared to new ones. [76] However, the avoided burden method based
3 GOAL AND METHODOLOGY

The intention of ZIN projects managers is to be as circular as possible in the transformation of WTC towers but so far, no solution other than recycling has been found for WTC towers glazing. The Chair of Circular Economy and Urban Metabolism of Brussels came with the idea of evaluating their potential of reuse on a greenhouse project. First, this idea is in the alignment with the goals of urban farming development in the region. Then, the idea of reusing these 14 000m² of glass panes in an urban greenhouse project appears as an opportunity for showing example of an ambitious circular project in Brussels. However, reusing a material in another function than the one it was made for can lead to a reduction in the quality of the new product that integrates it.

Therefore, the objective of this study is to discuss whether reusing WTC glazing is a more long-term sustainable option for growing tomatoes than investing in new professional glazing. Since WTC glazing units are tinted, are they suitable for such a project? Compared to a professional glazing, double glazing might appear as a way of saving the heating energy useful to tomato production as well as the production and transport of new glazing produced abroad. However, its light transmittance is lower and might seriously impact the crop yield. Is the solution of separating glass panes for only using the clear glass sheet a good option? The first part of our analysis will focus on answering these questions.

For this purpose, we will perform a comparative Life Cycle Assessment (LCA) of a greenhouse prototype in order to consider the environmental impacts of the whole lifespan. In addition to comparing reused to new building materials, the challenge is to include data related to the characteristics of the glazing in the LCA. These include its dimensions, its weight, but also its thermal and light performances. The strategy that will be applied in this work is the following:

1. Design a basic greenhouse prototype based on WTC glazing dimensions;
2. Defining different glazing scenarios of the glazing and apply them to the prototype;
3. Based on energy simulations, crop yield and material flow analysis, compare them by performing a comparative LCA;
4. Improving the prototype by exploring alternative scenarios for improving the resource-efficiency.
3.1 INITIAL SCENARIOS

In the objective of finding out whether reusing WTC glazing into a tomato greenhouse project would lead to a reduction of its environmental impacts, we will compare three scenarios: two scenarios of reuse and one scenario of new professional glazing. The three basic scenarios are:

1. **WTC double**: The double glazing is reused “as it is”, only the frame is removed. It is heavier so the foundations will be more important, and its light transmittance is lower so it will impact the yield negatively, but it is more insulating and will lead to a reduction in the heating demand.
2. **WTC simple**: In this scenario, we will only use the inside 10mm pane of the double glazing and leave the outside pane that is tinted. It is less insulating but has a higher light transmittance than the double glazing and will increase the surface heating demand, but also the crop yield.
3. **Professional**: This scenario uses professional glazing. Its thermal proprieties and light transmittance are similar to WTC simple glazing, but it is much lighter and will require smaller foundations.

The Life Cycle Inventory will consider various data related to the characteristics of the glazing in order to assess its quality to make a luminous and thermal atmosphere that is propitious to tomato harvesting. Therefore, it will consider:

1. Its surface mass impact on the dimensions of the metallic structure and on the foundations;
2. Its thermal proprieties and their impact on the yearly heating demand for keeping the greenhouse at an 18°C temperature;
3. Its light transmissivity and its impact on the crop yield.

3.2 LEVERS OF IMPROVEMENT

In the discussion, we will explore some levers of improvement on our prototype by modifying or adding some new parameters. The results of our LCA will allow us to identify the flaws in both reuse scenarios. Based on those results, the discussion will focus on two pathways for reducing their environmental impacts:

1. Reducing the heating demand of the greenhouse made of WTC simple glazing by changing some parameters in its scenario: increasing its size, reducing the harvesting season and integrating it to a building;
2. Improving the yield of double glazing by: adding some growing lights to WTC double glazing.

Finally, we will try one last alternative scenario with another type of double glazing with higher light transmittance.
4 PROTOTYPE DESIGN

The first step for comparing the environmental impacts of different greenhouse covering materials was to design a prototype in order to have some dimensions to work with in the further calculations.

The shape follows standard professional greenhouses construction models, and the dimensions were defined depending on WTC glazing, so it technically only needs minor operations for being reused. These include: cleaning of the glass, disassembly of the window’s frame, resizing of the triangular pane of the gable, and possibly the seal reinforcement.

The level of detail has been set to basic construction elements. It includes concrete foundations, a metallic structure, glazing covering, a rubber seal and screws. For simplification, and since we aim to focus on the performances of the glazing, it excludes all equipment such as ventilation fans, pipes, electrical lighting and harvesting system.

![Greenhouse prototype, image produced with SketchUp](image)

4.1 WTC GLAZING DATA

The dimensions of the model were defined by the WTC glazing units, that present the advantage of all having the same dimensions. Therefore, they offer the possibility of designing a greenhouse that is modular and can be extended or reduced following the user’s needs.

The glazing on WTC towers has never been replaced since 1973. The data provided by the real estate Befimmo indicates a total of:

- 5,247 glazing units;
- representing a surface of 14,000m² of glazing available;
• Each glazing unit measures 140x190cm;
• It is composed with two layers of glass separated by an air cavity forming a total thickness of 23.4mm (see Figure 34 in appendices);
• Its surface mass is 40kg/m² and each unit weights 106.4kg.

The 23.4mm panes are composed with one 6mm layer of bronze tinted coated glass, an 8.4mm air space and a 9mm coated clear glazing. Knowing this precise composition allows us to deduct its light transmissivity and thermal proprieties thanks to CalumenLive online tool.

It indicates a:
• Visible light transmittance of 38%;
• a U-value of 1.7W/m²K;
• an energy transmissivity of 24%.

For further details on the influence of bronze tint on PAR, we looked for a detailed spectrum graph. We found one given by Saint-Gobain glass factory on their bronze tinted glazing compared to a non-tinted glazing:

![Graph showing spectrum transmittance](image)

*Figure 12: Spectrum transmittance [59]*

The transmittance in the PAR is globally lower on the entire visible spectrum (400µm-700µm)

### 4.2 Construction choices: Fixed parameters

#### 4.2.1 Location

By simplification, the model is located on a flat and unobstructed surface, on a clay soil in Brussels. No precise location has been defined and the possibilities of implementing this potential greenhouse remain open to additional parameters and further research including local climate conditions.
However, we will see in the next chapters that the different reuse scenarios of the glazing already reduce the possibilities of implementation in some cases. This work will also explore the potential benefits of integrating the greenhouse on a rooftop.

### 4.2.2 Orientation

No specific orientation was defined for the greenhouse. In the mathematical model we used for estimating the heating demand of a greenhouse (see point 5.2.3.2), the orientation is simplified by considering that the glazing surface exposed to the sun is equivalent to the ground surface of the greenhouse.[77]

### 4.2.3 Shape

To design the prototype, we used simple constructive principles to make it dismantlable and reproductible in series. Even though different shapes like Dutch greenhouses, might offer extra growing surface for the same amount of glazing, we chose to use vertical walls so the model is modulable and can be extended easily into a multi-span greenhouse.

It is a standard gable greenhouse where the glass panes are reused in their entire dimensions, so they don’t have to be resized.

The suggested design is a FSGH with:

- 18,7m² ground area
- 49m³ volume
- 66,3m² glazing surface.

This would allow to build about 220 identical 18,7m² FSGH based on this model with the entire WTC supply.

The structure consists in a classical small greenhouse frame. Steel was chosen for the main structure for its robustness and recyclability, and an aluminium T-shaped profile was chosen for the frame holding the glazing. A robust material like steel allows the structure to be thin and maximize the light intake in the greenhouse.
It is made with prefabricated steel square tubes, aluminium T-shaped profiles and assembled with screws. All data concerning the products used were found in professional catalogues. The total length of tubes and profiles needed is 164.4m more about 700 screws, nuts and bolts.

All greenhouse scenarios have a ground L-shaped steel frame to fix them to their foundations. The foundations and the profiles of the structure will vary in function of the surface mass of the glazing used and will therefore be specific to each scenario (see point 5.1.4)
5 LIFE CYCLE ASSESSMENT

5.1 GOALS AND SCOPE

5.1.1 Objective
The aim of this study is to understand whether reusing WTC glazing, double or simple, used in a long-term tomato greenhouse project is a more sustainable choice than professional glazing. This means: is it suitable for maintaining an atmosphere that is propitious for plants growth? Using LCA, we will identify the most sustainable way to reuse the glazing, but also draw conclusions about the most adapted way to use this greenhouse based on its characteristics, compared to a professional glazing.

5.1.2 Functional unit
Knowing our objective to compare the environmental impacts of different glazing types used in a productive tomato greenhouse project, this work will focus on the glazing and its impacts on the growth rather than on the tomato production system itself. Therefore, our functional unit is: “the thermal and luminous atmosphere for producing one ton of tomatoes in an 18,7m² glass greenhouse heated at a temperature of minimum 18°C all year long in Brussels climate”

5.1.3 System boundaries
Greenhouses are complex systems where all the factors (presented in chapter 2.2) are deeply interconnected and can have an influence on each other as well as on the yield. Insulating some of them and focusing on the glazing is a methodological choice conscious that the result does not aim to predict realistic performances of the prototype.

This study will analyse the environmental impacts of our greenhouse from cradle to the end of its use phase. We did not make any assumptions concerning the end-of-life of the building materials, since most of them could still be either reused, recycled or landfilled. Therefore, the scope of this LCA will consider the material extraction, transport, extraction and 15 years use phase.

Since the objective of this study is to compare different types of coverings, we voluntarily simplified extremely complex models to only focus on the factors directly depending on the type of glazing used. Both climate data and glazing type will play a role in the crop yield of the greenhouse.

The scope of this LCA includes the data linked directly to the glazing used for each scenario. Therefore, we will consider these two quality standards for a productive greenhouse:

• Temperature in the greenhouse: in the literature and by asking professional horticulturist Nicolas Tytgat from Vastaculture, we found that the ideal temperature for growing tomatoes
was between 18°C and 26°C and should remain as constant as possible, with a delta max of 10°C per day.

- **Light transmissivity:** Most greenhouse plant crops do best when receiving about 70% to 80% of available light.[80] It is estimated that a decrease of 1% in the LT of the glazing of a greenhouse leads to a decrease of 1% in its productivity.[46]

Therefore, this study includes:

- **Material quantities:**
  - Glazing (in the scenario where glazing is reused, we will consider an avoided burden of the production of new professional glazing);
  - Concrete foundations;
  - Steel structure;
  - Screws;
  - Rubber seal for air tightness;

- **Construction:**
  - Transport;

- **Heat flow:**
  - Heat losses through glazing and ground;
  - Heat losses due to air exchange through the seals;
  - Heating energy gained from sun rays passing through the glazing;
  - Heating demand (natural gas);

And excludes:

- **Material quantities:**
  - Tomato harvesting process flows (water, fertilizer, waste);
  - Harvesting equipment;
  - Mechanical equipment (ventilation system, PVC pipes, water distribution system, electricity);

- **Construction:**
  - Construction process since all the WTC remanufacturing can be done by hand, only transport is considered;

- **Air emissions:**
  - CO₂, O₂;

- **Heat flows:**
  - Internal heat gains, due to simplification;
- Forced ventilation.

Table 3: Summary of parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Fixed/variable/neglected</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External Environ. parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily direct sunshine</td>
<td>Lux</td>
<td>Fixed</td>
<td>IRM</td>
</tr>
<tr>
<td>Outside temperature</td>
<td>°C or K</td>
<td>Fixed</td>
<td>IRM</td>
</tr>
<tr>
<td>Wind</td>
<td>m/s or km/h</td>
<td>Fixed</td>
<td>/</td>
</tr>
<tr>
<td><strong>Internal Environ. Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside temperature</td>
<td>°C or K</td>
<td>Fixed</td>
<td>-</td>
</tr>
<tr>
<td>Humidity</td>
<td>%</td>
<td>Neglected</td>
<td>-</td>
</tr>
<tr>
<td>Intensity of light</td>
<td>Lux</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Length of wave of light</td>
<td>nm</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>CO₂ concentration</td>
<td>ppm</td>
<td>Neglected</td>
<td></td>
</tr>
<tr>
<td><strong>Built Environ. Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td></td>
<td>Fixed</td>
<td>-</td>
</tr>
<tr>
<td>Orientation</td>
<td></td>
<td>Fixed</td>
<td>-</td>
</tr>
<tr>
<td>Shape</td>
<td></td>
<td>Fixed</td>
<td>Venlo type</td>
</tr>
<tr>
<td>Covering materials: heat transfer</td>
<td>W/m²K</td>
<td>Variable</td>
<td>WTC datasheet + St-Gobain</td>
</tr>
<tr>
<td>Covering materials: light transmittance</td>
<td>%</td>
<td>Variable</td>
<td>WTC datasheet + St-Gobain</td>
</tr>
<tr>
<td>Artificial lighting</td>
<td>Lux</td>
<td>variable</td>
<td>Lumigrow</td>
</tr>
<tr>
<td>Ventilation</td>
<td>1/volume</td>
<td>Fixed</td>
<td>-</td>
</tr>
</tbody>
</table>

5.1.4 Definition of the scenarios

In order to perform the LCA, different reuse scenarios must be established to compare their impacts. Through these different scenarios, the idea is to question different aspects of its design in order to make the most sustainable choice:
5.1.4.1 **Reused double-pane WTC glazing**

- The whole covering is made of WTC glazing, but the tinted pane is placed on the inside of the greenhouse, increasing light transmissivity.
- Remanufactured in Brussels by hand and transported on 10km, then assembled.
- The glazing being heavy (40kg/m²), it requires a thick structure. Our choice has been set on a 60x60mm steel tubes.
- Foundations dimensions are similar to verandas, with concrete strip foundations and a L-shaped steel profile frame on the whole perimeter of the GH and 40x40x20cm concrete studs under each support. (see Figure 35 in appendices).

![Figure 15: 3D model of WTC double scenario, image produced with SketchUp](image)

5.1.4.2 **Clear side of WTC glazing:**

- The WTC double-glazing panes are separated. The tinted pane goes to recycling and the clear pane is reused in the greenhouse (10mm, 25kg/m²).
- The glass remanufacturing is done by hand and transported on 10km.
- The steel profiles used for the structure dimensions are 50mm x 50mm with a 3mm thickness.
- Foundations are lighter, similar to a typical glazed garden greenhouse with a concrete strip foundation and a L-shaped steel profile frame on the whole perimeter of the GH and 20x20x20cm concrete studs under each support.
5.1.4.3 Professional

- 100% of the covering is made with Albarino Mid Haze (4mm, 10kg/m²) from Saint-Gobain factory in Germany
- We considered a transport by truck on 400km
- The glazing is much lighter, so the structure is made of steel profiles of 40mm x 40mm and 3mm thickness
- Since the whole greenhouse is lighter, only some steel studs and a very small concrete foundation footing is needed in addition to the L-shaped steel profile frame.
5.1.5 Methodological choices

Our calculations were made the Ecolinvent 3 database on Simapro software. We used the standard ReCiPe 2016 Hierarchist method for calculations.

We chose the consequential allocation method since is seemed as a theoretically correct model to treat multifunctional processes and recycling.[74] We included the 66,3m² of reused glazing dividing its environmental impacts on its entire extended lifespan (45 years in WTC towers + 15 years in a greenhouse) and considered an avoided burden of the same surface of horticultural glazing.
5.2 **LIFE CYCLE INVENTORY**

5.2.1 **Construction materials**

As defined in the prototype design, the level of detail is set to basic construction elements for a freestanding greenhouse in open ground.

The input material that determines the rest of the structure is the glazing we used. As explained in the definition of the scenarios in point 5.1.4, the structure and the foundations have been adapted to the weight of each glazing used.

Following our calculations, here are the total quantities of material for one entire 18.7 m² greenhouse with a 15 years lifespan:

*Table 4: Material quantities for an 18.7 m² greenhouse*

<table>
<thead>
<tr>
<th>Material</th>
<th>WTC double</th>
<th>WTC simple</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing (23.4mm)</td>
<td>2 652kg</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Flat glazing (10mm)</td>
<td>/</td>
<td>1 657kg</td>
<td>/</td>
</tr>
<tr>
<td>Low-iron glazing (4mm)</td>
<td>/</td>
<td>/</td>
<td>663kg</td>
</tr>
<tr>
<td>Lean concrete (2200kg/m³³)</td>
<td>1,064m³</td>
<td>0,448m³</td>
<td>0,196m³</td>
</tr>
<tr>
<td>Steel for foundations</td>
<td>294kg</td>
<td>294kg</td>
<td>294kg</td>
</tr>
<tr>
<td>Steel structure</td>
<td>940kg</td>
<td>734kg</td>
<td>561kg</td>
</tr>
<tr>
<td>700 screws</td>
<td>1.7kg</td>
<td>1.7kg</td>
<td>1.7kg</td>
</tr>
<tr>
<td>168m of rubber seal</td>
<td>2.8kg</td>
<td>2.8kg</td>
<td>2.8kg</td>
</tr>
</tbody>
</table>

Each of these materials was included to the LCA considering their total lifespan:

*Table 5: Lifespan considered for the building materials*

<table>
<thead>
<tr>
<th>Material</th>
<th>Lifespan</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTC Double glazing</td>
<td>60 years</td>
</tr>
<tr>
<td>WTC Simple glazing</td>
<td>60 years</td>
</tr>
<tr>
<td>Professional glazing</td>
<td>15 years</td>
</tr>
<tr>
<td>Lean concrete</td>
<td>15 years</td>
</tr>
<tr>
<td>Steel Structure</td>
<td>15 years</td>
</tr>
<tr>
<td>Steel for foundations</td>
<td>15 years</td>
</tr>
<tr>
<td>Screws</td>
<td>15 years</td>
</tr>
<tr>
<td>Rubber seal</td>
<td>5 years</td>
</tr>
</tbody>
</table>
5.2.2 Transport

Due to a lack of information and since most of the glass remanufacturing can be done by hand\textsuperscript{2} we neglected the treatment and the construction process and only considered the transport.

We assumed that WTC glazing would remain in a perimeter of 5km around the towers and doubled this number since they will most likely be stored before being reused, so will travel twice.

Concerning the professional glazing, the one we chose is produced in Saint-Gobain factory in Mannheim. That represents a journey of about 400km from the factory to Brussels.

\textit{Table 6: Kilometers of road transport considered for each type of glazing}

<table>
<thead>
<tr>
<th>WTC double</th>
<th>WTC simple</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>10km</td>
<td>10km</td>
<td>400km</td>
</tr>
</tbody>
</table>

5.2.3 Heating demand

Heating demand was estimated with a mathematical model that includes local climate conditions (daily sunshine, temperature), the basic dimensions of the greenhouse (ground area, volume, glazed surface) and the main characteristics of a glazing.

5.2.3.1 Brussels climate data

Average temperature and daily sunshine have a major influence on the temperature inside the greenhouse. A good knowledge of the local climate is essential when designing a greenhouse. The data used was collected at the Institut Royal Météorologique (IRM) in Uccle and presents the average temperature and sunshine hour per hour on a whole year period between 1981 and 2010. [81]

The raw data is presented as an 8760 lines table containing hour by hour data on the whole year period concerning:

- the average outside temperature;
- direct perpendicular and diffuse sun rays;
- global sunshine on a horizontal surface;
- daily duration of sunshine;
- absolute humidity;
- wind speed.

Our methodological choice has been to treat this raw information (see Table 9 in Appendices) in order to have an average data for the outside temperature and global sunshine on a horizontal surface

\textsuperscript{2} Information communicated by Olivier Breda from DZEROSTUDIO, architect of the Tomato Chili greenhouse project
hour by hour and month by month (see Table 10Table 11 in Appendices). This allows a level of detail to make appear some nuanced contrast for each period of the year, identify the critical periods of the day and the night for overheating and heat losses, and yet establish easy annual averages for heating demand.

5.2.3.2 Mathematical model for yearly heating demand

We evaluated the thermal performances per month, based on a mathematical model used, calculation of the quantity of heating in Megajoules [MJ] needed for maintaining a minimal temperature of 18°C in the greenhouse.

The mathematical model for greenhouse heating demand estimation comes from a work done at the Energy Science and Technology ETHZ school in 2009. This model uses various data concerning local climate, the characteristics of the glazing and the shape and surface of the greenhouse to give an estimation of the yearly heating demand of a greenhouse. The results in MJ are can be used as an input in an LCA.[77] It is based on the formulas:

\[
Q_{\text{heat}} = (Q_{\text{trans}} + Q_{\text{air}}) - \alpha(Q_{\text{solar}} + Q_{\text{internal}}), \text{ [MJ]}
\]

\[
Q_{\text{trans}} = \sum k_i A_i (T_{\text{in}} - T_{\text{out}}), \text{ [W]}
\]

\[
Q_{\text{air}} = n V (\rho c_p) (T_{\text{in}} - T_{\text{out}}), \text{ [W]}
\]

\[
Q_{\text{solar}} = G A_w (f_h \tau f_s), \text{ [W]}
\]

This model matches our goal which is to estimate whether the glazing is suitable for maintaining the greenhouse at a stable temperature. Based on the monthly hour by hour average local climate data, it allows to identify precisely when and how much the greenhouse will be losing or gaining energy.

Definition of the parameters

- **Ground area** \(A_{\text{ground}}\) = from the model: 18,7m\(^2\)
- **Glazing surface** \(A_{\text{tot}}\) = from the model: 66,3m\(^2\) of glazing
- **Volume** \(V\) = from the model: 49m\(^3\)
- **Temperature outside** \(T_{\text{out}}\): in function of the meteorological monthly averages hour by hour results
- **Temperature inside** \(T_{\text{in}}\): set to 18°C, which is considered in the literature as the minimal temperature for tomato growth, usually chosen by professionals
- **Ground temperature** \(T_{\text{ground}}\): we added a parameter for ground temperature since our FSGH is in the open ground. The data come from énergie+ website and gives a monthly average of the ground temperature in Brussels
• **Solar irradiation (G):** the amount of sun energy reaching the ground (W/m²), found in the hour by hour average IRM data.

• **Heat through component (U_value):** is the amount of heat transmitted through the glazing. The data used comes from a model of each sort of glazing on CalumenLive online tool.

• **Heat exchange number (n):** the amount of times the air volume inside the greenhouse is renewed per hour. We defined it as 1, which is the natural ventilation of a correctly built glass greenhouse through the air gaps in the covering. The choice of a constant can be discussed. Indeed, it is unfavourable to the WTC double glazing scenario, that is probably more impervious than the simple glazing scenarios. Furthermore, we excluded forced ventilation, which is quite unrealistic in the scenario of a productive greenhouse.

• **Specific volumic energy air constant (ρcp):** 0.32, as defined in the model. [77]

• **Glass fraction of the window (fg):** proportion of glaze surface compared to the total surface of the window, we defined is at 0.9 since we considered that the window frames were removed and only the glazing, its seal and the structure of the greenhouse remain.

• **Reduction factor (fs):** defined as 0.6, as defined in the model. [77]

• **Light transmissivity (τ):** is the amount of solar light transmitted by the glazing compared to the amount reflected, defined using “Light Transmissivity (%)” value from CalumenLive.

• **Solar heat gains coefficient (α):** amount of solar heat passing through the glazing, defined by using the “Energy Transmissivity (%)” value from Calumen Live.

<table>
<thead>
<tr>
<th>WTC double</th>
<th>WTC simple</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>47046 MJ</td>
<td>94853 MJ</td>
<td>97271 MJ</td>
</tr>
</tbody>
</table>

**Table 7: Yearly heating demand for an 18.7m² greenhouse**

5.2.4 **Crop yield**

It is commonly considered among professional growers that a decrease of 1% in the visible light transmittance of a glazing leads to a decrease of 1% in the crop yield of a greenhouse. We found confirmation for this rule in the literature and looked closer into the PAR transmittance of a bronze glazing compared to a clear glazing and decided to apply it to our model. We insist again on the fact that this is a theoretical model for establishing a proportional measurement of the potential productivity of a greenhouse and compare different types of glazing materials. In no case do we aim nor pretend to make a prediction of the actual yield of the greenhouse. This would require incredibly more complex calculations taking into account many more parameters than we did.
Therefore, our inventory has reported every data collected to a fictive ton of tomato that would be produced in the greenhouse, to assess the theoretical proportion of glazing, steel, concrete, heating, rubber and transport that contributes to the process.

We assigned a yield of 50kg/m² for the professional glazing greenhouse scenario, which is the equivalent to an optimistic yield for a professional hydroponics tomato greenhouse. We adapted this number in function of the decrease in LT for each scenario.

In other terms, standard professional greenhouse glazing has a LT of 91% and is assigned the maximal yield of 50kg of tomatoes per m² per year. This represents 935 kg of tomatoes per year for the 18,7m² GH. The glazing in our “WTC simple” scenario has an 89% LT, this means that it has a 2% inferior yield. “WTC double” glazing has a 38% LT, that means a 53% lower yield.

Table 8: Definition of the crop yield for each scenario in tons of tomatoes per year for an 18,7m greenhouse:

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>WTC double</th>
<th>WTC simple</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Light Transmittance (LT)</td>
<td>38%</td>
<td>89%</td>
<td>91%</td>
</tr>
<tr>
<td>Surface yield</td>
<td>23,5kg/m²</td>
<td>49kg/m²</td>
<td>50kg/m²</td>
</tr>
<tr>
<td>Total yield</td>
<td>0,44 ton</td>
<td>0,91 ton</td>
<td>0,93 ton</td>
</tr>
</tbody>
</table>

5.3 RESULTS

All the collected data from the construction materials, transport and heating demand were reported to the equivalent of the production of one ton of tomato and entered in SimaPro software.

By comparing the endpoints results for our three basic scenarios, we observe that the scenario of the greenhouse made with “WTC double” glazing presents the highest environmental on all human health, ecosystems and resources, despite that it is made from reused materials and presents a lower heating demand per m² than the two other scenarios.
The professional glazing scenario comes second in terms of highest environmental impacts in all endpoints, and WTC simple comes last.

Figure 18: Comparison of the environmental impacts of the luminous and thermal atmosphere propitious to the growth of 1 ton of tomatoes, for professional glazing scenario (dark green), WTC double scenario (light green) and WTC simple scenario (orange). Chart exported from SimaPro (%)

To understand these results, let’s start by looking into the detailed source of these impacts for all three scenarios. It appears that the main contributor is, in each case, the heating demand. This is, indeed, not surprising since we considered the greenhouse on its entire lifespan (15 years) and that it is heated at 18°C.

Figure 19: Contribution to the environmental impacts of the luminous and thermal atmosphere propitious to the growth of 1 ton of tomatoes for WTC double scenario: Heating (red), steel structure (dark blue), reused glazing (green) and avoided burden of new glazing (burgundy). Chart exported from SimaPro (%)

In this more detailed inventory (image above) of the source of the impacts of WTC double greenhouse scenario, we notice that heating (in red) represents the largest part in the impacts all in human health (80,5%), ecosystems (89,3%) and resources (95,4%).

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The steel used in the structure represents the second largest part in the environmental impacts: 15.7% in human health, 8% in ecosystems and 3.7% on resources.

Glazing (light green) comes third since that, even if it is reused and we considered a lifespan of 60 years, it still shows higher environmental impacts than the ones avoided by not producing a new horticultural glazing. This shows the flaws of using the avoided burden method in our reuse case where the new material is more lightweight than the reused one and, therefore, does not fully compensate the impacts of the production of the old material.

Figure 20: Contribution to the environmental impacts of the luminous and thermal atmosphere propitious to the growth of 1 ton of tomatoes for WTC simple scenario: Heating (red), steel structure (dark blue), reused glazing (green) and avoided burden of new glazing (burgundy). Chart exported from SimaPro. (%)

In the detailed repartition of the environmental impact’s sources for the WTC simple scenario, we notice that steel represents a smaller part of the graphs than for WTC double scenario. Heating still fills the largest part of the graphs and the avoided burden of new glazing production still shows in human health and ecosystems endpoints.
Figure 21: Contribution to the environmental impacts of the luminous and thermal atmosphere propitious to the growth of 1 ton of tomatoes of professional glazing scenario: Heating (burgundy), steel structure (dark blue) and new glazing (green). Chart exported from SimaPro. (%)
5.3.1 Importance of considering the heating demand

We compared the environmental impacts for 1m² of WTC simple glazing scenario greenhouse with and without heating. They are 90% lower on human health endpoint, 95% lower on ecosystems and 98% lower on resources.

Figure 22: Comparison of the environmental impacts of 1m² of an 18,7m² heated tomato greenhouse and an 18,7m² unheated greenhouse. Chart exported from SimaPro. (%)

In this case, not considering neither the heating demand nor the yield, but only the greenhouse surface really gives the advantage to the WTC simple scenario. Indeed, it has the advantage of not requiring a structure as heavy as the WTC double greenhouse, and to avoid the production and transport of a new professional glazing. The scenario with new professional glazing comes first in the environmental impacts on ecosystems.

Figure 23: Comparison of environmental impacts of 1m² of an 18,7m² unheated tomato greenhouse for professional glazing scenario (dark green), WTC double scenario (light green) and wtc simple scenario (orange). Chart exported from SimaPro. (%)

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5.3.2 Importance of considering the yield

By comparing one m² of heated surface, we can see that the results are completely different than when we include the yield of the greenhouse to our calculations. Indeed, since the largest proportion of the impacts comes from the use phase, the results are proportional to the heating demand calculated in our Life Cycle Inventory. Here, WTC double scenario presents much lower environmental impacts than the two other scenarios.

![Figure 24: Comparison of environmental impacts of 1m² of an 18,7m² heated tomato greenhouse for professional glazing scenario (dark green), WTC double scenario (light green) and wtc simple scenario (orange). Chart exported from SimaPro. (%)](image)

To sum up, considering the heating demand and the yield of our greenhouse really was a game-changer in the results. The choice of “the thermal and luminous atmosphere for producing one ton of tomatoes in an 18,7m² glass greenhouse heated at a temperature of minimum 18°C all year long in Brussels climate” really reverses the outcome of the study.

When we exclude the parameter of the yield from the LCA, a clear advantage appears for the WTC double scenario. However, without considering the use phase, there is a clear advantage for the WTC simple scenario.

In the end, by considering the construction materials, the use phase and the yield, the gap between the three scenarios gets smaller. This means that, on a use phase of 15 years, the difference in the embodied energy and in the heating demand per surface is compensated by the impact of the glazing material on the yield.

Yet, the advantage remains for WTC simple scenario, due to a higher LT and a smaller steel structure than the WTC double scenario, and a slightly lower heating demand the environmental benefits of reusing glazing compared to the new professional glazing scenario.
6 DISCUSSION

In this discussion, we will explore some ways to make our prototype more resource and energy-efficient. Indeed, the definition in the details of our prototype remained low, making it open for improvement. In this chapter, we will modify some of our parameters, or add some new ones, in order to give some levers of improvement for our greenhouse.

We demonstrated previously that both light transmissivity and heating demand can have a tremendous effect on the environmental impacts of a tomato greenhouse yield. Therefore, these alternative scenarios will focus the reuse scenarios flaws: reducing the heating demand for WTC simple scenario and increasing the luminosity in WTC double scenario.

6.1 REDUCING THE HEATING DEMAND PER m²

In this point, we aim to investigate different ways to reduce the heating demand by questioning the size, the location or the use of the greenhouse. What is the difference in the impacts if the greenhouse is bigger? Or located on a roof? Since the aim here is to push the WTC simple scenario by reducing its heating demand, we conducted some simple comparative LCAs to evaluate whether some changes were positive to the process. This will allow us to draw some conclusion about ways to improve our prototype into being less energy-intensive.

6.1.1 Extending the ground surface of our greenhouse

In the literature, we noticed a considerable difference between the heating needs of our greenhouse compared to professional ones.[66] We found that the average tomato GH needs about 1400MJ/m², but our results indicate a heating demand of about 5000MJ/m².

This difference can be explained by the fact that we had a strict rule to never let our greenhouse under the temperature of 18°C without considering its thermal inertia, which means that it is heated every hour of the year where the outside temperature and sunlight does not bring the greenhouse to this temperature. Another explanation is the small size of our prototype. In fact, it:

- Had us consider heat losses through the ground, since it is small and not insulated
- Proportionally has a larger surface of glazing compared to its ground area. Increasing the size of the greenhouse (like professional greenhouses), allows us to occupy a larger harvesting surface compared to its external covering surface.

In this improvement scenario, we decided to multiply the ground area of our greenhouse by 96. This alternative prototype now has a total glazing surface of 2937m² for a 1795,2m² ground surface.
This means a ratio of Glazing/Ground area of 1.63 compared to our smaller greenhouse that has a ratio of 3.54. The yearly heating demand lowers to 1700MJ/m² in the larger GH.

![Comparison of environmental impacts](image)

*Figure 25: Comparison of environmental impacts of the thermal and luminous atmosphere propitious to the production of 1 ton of tomatoes in a heated greenhouse made with WTC simple glazing: with a ground surface of 18.7m² (dark green) and 1795m² (light green). Chart exported from SimaPro. (%)*

It is no surprise than this brings a reduction of 62% of the environmental impacts of one ton of tomatoes produced in the bigger greenhouse, in all Human Health, Ecosystems and Resources endpoints in our LCA comparison. Therefore, we do not recommend small-scale heated greenhouse agriculture as a sustainable solution.

### 6.1.2 Opening the greenhouse 9 months per year

As explained in point 0, all-year-long tomato popularity in Belgium leads to high environmental impacts for winter tomatoes, that either come from Spain or are grown locally but in an 18°C heated GH when the average outside temperature is 3°C. The months of December, January and February are the darkest and the coldest of the year and this is when the greenhouse heating demand is the highest.

According to our calculations, closing our tomato GH for 3 months in the Winter (Dec-Jan-Feb) can lead to a reduction of 48% in its yearly heating demand. If we consider that our artificial climate
brings an even production all year long, this would mean a reduction of 25% in our yearly tomato production.

![Comparison of environmental impacts](image)

*Figure 26: Comparison of environmental impacts the thermal and luminous atmosphere propitious for the production of one ton of tomatoes in an 18.7m² heated greenhouse made with WTC simple glazing open all year long (dark green) and closed in the wintertime (light green). Chart exported from SimaPro. (%)*

Therefore, a significant reduction of the impacts of yearly tomato production by ton can be observed in the LCA. Our results indicate a 28% reduction in the environmental impacts in Human Health, 31% in Ecosystems and 33% in Resources.

If the objective of building that greenhouse is to remain productive all year long, another solution for reducing its heating demand is to adapt the crop in function of the season.

It is commonly advised not to grow any other plants than tomatoes at the same time in the same greenhouse.[60] Therefore, this alternative considers that tomatoes are only grown during the warm season, and lettuce, that require a temperature of 10°C, are grown during the cold season.

![Heating demand](image)

*Figure 27: heating demand for an 18.7m² greenhouse built with WTC simple glazing and heated at 18°C all year long (blue) or at 10°C from October to May (red)*
Following our calculations, heating the greenhouse made with our clear 10mm thick glass pane from WTC at a temperature of 18°C from May to October [83] (the greenhouse keeps receiving natural heat from the ground thermal inertia until October) and a temperature of 10°C between November and April could bring a reduction of 44% in the yearly heating demand.

### 6.1.3 Building integrating our GH

In the calculations for our FSGH, we took into account the heat losses through the ground. For the WTC simple scenario, these represent 18 189 MJ per year, on a total of 82 637 MJ per year for the 18.7 m² greenhouse. In other terms, 22% of the greenhouse heat is lost in the ground.

![Heat losses](image)

*Figure 28: % of heat losses of an 18.7m² FSGH in Brussels*

In this alternative scenario, we considered that our greenhouse was located on a roof of a residential building heated at a temperature of 20°C, with a U-value of 5.4 W/m²K [84], and benefits from the heat losses of the building. We did not consider the benefits of the greenhouse for the building.

![Comparison of environmental impacts](image)

*Figure 29: Comparison of environmental impacts of 1m² of an 18.7m² heated tomato greenhouse: Heated at 18°C in open ground (dark green), RTG heated at 10°C (light green) and RTG heated at 18°C (orange). Chart exported from SimaPro. (%)*
If we assume that the building it’s integrated to is heated at a temperature of 20°C, the choice of changing the location of the GH from an open ground to a rooftop could allow to reduce the heating demand of the GH of about 7 757 MJ per year. Therefore, this would reduce the environmental impacts of about 20% on human health, ecosystems and resources.

6.2 INCREASING THE LUMINOSITY & THE PRODUCTIVITY

The results of our LCA showed that the major problem of the WTC double glazing concerns its luminosity and its effect on plant growth. Therefore, we developed a scenario where LED growing lights are added to the greenhouse to increase its yield and make it more resource-efficient. Finally, one last scenario where we compare WTC double glazing to a new standard double glazing.

6.2.1 With artificial light

As explained in point 2.2.3.5, artificial lighting can be a solution for improving the yield in a greenhouse when the luminosity is too low. In this scenario we compared the environmental of one ton of tomatoes produces in a greenhouse made with WTC double glazing, with and without artificial growing lights.

![Figure 30: Comparison of environmental impacts the thermal and luminous atmosphere propitious for the production of 1 ton of tomatoes in an 18,7m² heated greenhouse made with WTC double glazing: without growing lights (dark green) and with growing lights (light green). Chart exported from SimaPro. (%)](image)

We chose Lumigrow LED light that has an energy consumption of 325 Watts, and that can increase the yield by 30% when lit for a photoperiod of 12 hours a day.[85] We did not consider the environmental impacts of the device in itself but we considered an extra electricity consumption of 60,4kWh per year and an increase of 30% in the yield.

In the LCA results, we see that adding electricity consumption for improving the yield is a positive addition the process by making the tomato production more resource-efficient. Indeed, it leads to a...
reduction of 5% in the environmental impacts on human health, 10% on ecosystem and 20% in on resources.

6.2.2 With a different double glazing

Finally, it is important to remind that WTC glazing units the advantage of being all even-dimensioned and available in a large quantity, but they are particularly dark tinted and that it is not the case of all double glazing.

In this final test, we tried applying a more recent standard double glazing (CLIMAPLUS) to our prototype and compared it to the old WTC double glazing scenario. This new glazing is composed of two 4mm layers of clear glass and a 16mm argon cavity. It has a LT of 80% and a U-Value of 1 W/m²K. It is also much lighter than WTC double glazing (20 kg/m²). Therefore, we used the same structure and foundations than for WTC simple scenario.[64] All data was estimated by using CalumenLive tool.

Tableau 5: Differences in heat transfer, surface mass and light transmittance of WTC double and CLIMAPLUS glazing

<table>
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<th>WTC double</th>
<th>CLIMAPLUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Value</td>
<td>1.7 W/m²K</td>
<td>1 W/m²K</td>
</tr>
<tr>
<td>Surface mass</td>
<td>40 kg/m²</td>
<td>20 kg/m²</td>
</tr>
<tr>
<td>LT</td>
<td>38%</td>
<td>80%</td>
</tr>
</tbody>
</table>

In this final test, it follows that using new clear double glazing for 15 years in a tomato greenhouse leads to 60% less of the environmental impacts than reusing WTC double glazing. This is explained by the fact that this new double glazing presents a high light transmittance and a low U-Value, making it extremely energy-efficient for tomato growth.

Figure 31: Comparison of environmental impacts of the thermal and luminous atmosphere protitious for the production of 1 ton of tomatoes in an 18.7m² heated greenhouse made with CLIMAPLUS glazing (dark green) and WTC double glazing (light green). Chart exported from SimaPro. (%)
6.3 Prospects for future research

Our results indicate that a more common type of double glazing can lead to an increase in the yield and a reduction in the heating demand compared to WTC double glazing. On a circular point of view, this statement puts our work in perspective in the sense that it raises the question of the urban mining and the assessment of the building material stock in Brussels. Indeed, what if they were another office building in Brussels that was undergoing a deep renovation at the same time and casted aside another important quantity of glazing but with a better LT or U-value? Meanwhile, would another architect be interested in finding a glazing with a low Light Transmittance to reuse as a sun screen in a new building, like in Figure 42?

When evaluating the potential of reuse of a glazing for a greenhouse project, knowing the precise characteristics of the input material is crucial in order to model different reuse scenarios. We would never have come with the WTC simple scenario before knowing that one of the two layers of glass was not tinted. We believe that, in order to make a circular and sustainable greenhouse project with such quantities of glazing, some comparative studies should be conducted on regional scale to evaluate different sources of glazing.

However, our experience conducting this project showed that the exchange of information on the building materials of the WTC towers was complicated. Indeed, the question of the reuse of the glazing was no longer relevant for the project managers and it took an incredible amount of time to receive the glazing information we needed to start our project. More than three months passed between the moment where the Chair in Circular Metabolism made the demand for a datasheet of the glazing, and the moment we received it. The access to the towers was forbidden, and nothing could be found in the archives since the existing original documents were in the hands of the owners of the towers.

Including reused content in an architecture project requires comparative research and preliminary evaluations of the input material. In a highly dynamic construction and deconstruction sector, this tardiness in the access to the information of a building material about to waste is problematic. However, can we expect from the different stakeholders to individually exchange the technical specificities of their glazing? Currently, an online building material exchange platform exists, but the characteristics of the materials are not systematically given.[86]

So far, the building material stock and CDW mass has been estimated [87], but no detailed evaluation of the glazing stock has been made yet. Aristide Athanassiadis, researcher at the Université Libre de Bruxelles and co-director of the Chair in Circular Metabolism, already developed a bottom-up methodology for mapping the building material stock of Melbourne. Could this method be applied to
Brussels? On the other hand, tools exist that can analyse the composition of a glazing and instantly export its characteristics.[88] Further research might want to consider to make an inventory of quantity and the quality of available glazing in BCR. We believe that an easier access to information about the quantity and the quality of Brussels glazing stock would increase chances to find most sustainable outcomes for end-of-life glazing.
CONCLUSION

Principles of circular economy imply that the environmental challenge can only be met through stakeholder collaboration. The ecological transition is a multi-sector and multi-scale work. In this thesis, we intended to bring together two important sectors of the environmental transition: urban agriculture and circular economy of construction and demolition waste.

In the end, the most important point demonstrated in this work is that reusing a construction material does not always lead to a reduction of environmental impacts. The use phase represents most of the environmental impacts of a greenhouse that is built for 15 years. Considering the characteristics of the glazing brings in an element that cannot be neglected: the quality of the material used in a different function can easily backfire into higher environmental impacts than the ones avoided by embodied energy savings. Greenhouses have specific needs that must be considered starting from their design phase. One should be careful and understand the characteristics of a glazing before deciding to reuse it in a productive greenhouse project.

Between our three initial scenarios, reusing the WTC double glazing “as it is” turns out to be quite an unrecommendable option due to its poor light transmissivity. Indeed, it has a negative impact on the yield, giving its crop higher environmental impacts than tomatoes grown in a simple glazing greenhouse, even though the heating demand per square meter is lower. However, reusing the clear glass pane of the WTC windows presents lower environmental impacts than a professional glazing. This can be explained by the fact that it extends the lifespan of a glazing that is already 45 years old, avoiding the production of a new glazing material, and it has a light transmittivity that is nearly equal and a higher U-value than a professional covering material.

In terms of embodied energy, considering the effects of the mass of the glazing on the greenhouse structure, as well as choosing steel as a material, gave an advantage to lighter covering materials. Reusing glazing in the case of the WTC simple glazing scenario compensates the fact that it needs a heavier structure than the professional glazing. To reduce the environmental impacts of the construction materials, we would recommend finding a more sustainable structure material, like wood or reused metal.

Considering the heating demand was essential in the outcome of our analysis, since it represents about 90% of the environmental impacts of the greenhouse on its entire lifespan. In our research for reducing its heating demand, the first observation is that the dimensions of the greenhouse have a significant importance. Indeed, the ratio between the glazed surface and the ground surface being higher, our prototype happens to be way more energy-intensive than actual hectares professional
tomato production greenhouses. Using a very small prototype might have been a misleading since its yearly heating demand is much higher than professional greenhouses. This leads us to question the existence of individual heated greenhouses in private gardens. Placing the greenhouse on a building heated at 20°C can also lead to a reduction in its heating demand. The only heat gains from the building roof to a greenhouse heated at 18°C can decrease the heating demand by 22%.

Then, changing the management of the greenhouse, for example by accepting the fact that it could be closed during the winter, or adapting the production in function of the season can also drastically lower its environmental impacts by reducing its heating demand. Closing our greenhouse during the three coldest months of the year leads to a reduction of 50% in its yearly heating demand. Lowering its temperature to 10°C and use it to produce different vegetables in the winter lowers its heating demand by 44%, and up to 100% when the GH is made of double glazing. Further research could be conducted for assessing the Life Cycle Cost of our tomato greenhouse to see if adapting the crop in function of the season is a viable solution for its user.

Furthermore, increasing the yield by using artificial lights can lead to a reduction of the environmental impacts of the tomato production by making it more resource-efficient. This part of the study is to be taken cautiously since we did not consider the embodied energy of the lights but only the extra-electricity used and a yield improvement of 30%.

Finally, this study does not aim to exclude double glazing as an option for building a greenhouse. WTC glazing is a particular case because of its bronze tinted sun protection. Our last alternative scenario comparing WTC glazing to a more recent double-glazing shows that finding a glazing with higher light transmittance and lower U-value can be a win-win situation.

Choosing a functional unit including the light transmissivity of glazing and its impact on the yield in addition to its thermal proprieties helped proving the nonsense of reusing tinted double glazing. This would not have shown in an LCA that would only consider the heated greenhouse surface without taking into account their quality for its repurposed function.

On a micro level, this brings us to consider our choice of tomatoes for our greenhouse. Their consumption hides a highly energy-intensive process, especially off season when they must be either imported from Southern Europe or produced in heated greenhouses. This choice was initially carried by the large amount of information available on the subject and to test our scenarios under an important delta of temperatures in order to reveal their thermal performances, but also because tomatoes remain extremely popular in Belgium, even during the cold season. It is a common misconception that the productivity of Brussels hinterland stops in the winter. Many vegetables can still
be produced locally, without requiring large amounts of energy to re-create an artificial Mediterranean climate in January when the average outside temperature is 3.7°C.

At a macro scale, our last alternative scenario indicates that another type of double glazing might lead to better results than any form of WTC reuse scenario. The fact that there is currently no data available concerning the glazing stock in the Brussels Capital Region appears as a crucial missing piece in our reflection. Indeed, why focus on reusing WTC stock when other CDW glazing could lead to a better yield and lower energy consumption? Further interesting research might want to evaluate the current quantity and the quality of glazing stock available in the Brussels in order to find the best “mix-match” scenario for reusing glazing at a local scale and extending its lifespan.

By studying a micro-scale case of repurposing one predefined glazing into one predefined function, we might have found a slightly better option of reducing the environmental impacts of an urban tomato greenhouse in BCR, but did we find the best one? The results of our last alternative scenario imply that there is a possibility that the answer to this question is “no”. The environmental transition is a multi-sectorial and multi-scale challenge, and a good knowledge of Brussels glazing stock appears as a key to making well-informed decisions that will create strong connexions between different sectors and lead to a general transition towards a circular economy integrated to our cities.
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[87] Athanassiadis A, Bouillard P. Contextualizing the urban metabolism of Brussels: correlation of resources use with local factors, Université Libre de Bruxelles, (2013).

APPENDICES:

Figure 32: Commercial article for Brussels WTC (1973), found in C.I.V.A Archives
Figure 33: Manhattan Plan for Brussels North district [24]
### Table 9: Sample of IRM records of the average climate between 1981 and 2010 for January 1 and 2

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Tableau 6: Average temperature and sunshine recorded at the IRM of Uccle between 1981 and 2010

Average temperature and sunshine

- Average temperature [°C]
- Average daily sunshine [W/m²]
Table 10: Average hourly temperature recorded at IRM between 1981 and 2010

![Average hourly temperature [°C]](chart10)

Table 11: Average hourly sunshine on a horizontal surface recorded at the IRM between 1981 and 2010

![Average hourly sunshine on a horizontal surface [W/m²]](chart11)
Figure 34: Original construction detail of WTC glazing, provided by Befimmo and transferred by Mathieu Depoorter from ECORES

Figure 35: Example of foundation for a veranda [89]
Figure 36: Characteristics of WTC double glazing, produced with CalumenLive tool

Figure 37: Characteristics of WTC simple glazing, produced with CalumenLive tool
**Figure 38:** Characteristics of professional glazing, produced using CalumenLive tool

**Figure 39:** WTC double scenario: Detail of the environmental impacts of an unheated greenhouse per m². Blue: Steel, Orange: Concrete, Green: Reused glazing, Red: Avoided burden of new glazing material.
Figure 40: WTC simple scenario: Detail of the environmental impacts of an unheated greenhouse per m². Blue: Steel, Orange: Concrete, Green: Reused glazing, Red: Avoided burden of new glazing material.

Figure 41: Professional glazing scenario: Detail of the environmental impacts of an unheated greenhouse per m². Blue: Steel, Orange: Concrete, Green: new glazing, Red: Road transport.
Figure 42: Façade of “Forum 3” building on the Novartis Campus in Basel. A tinted glazing curtain is used as a sunscreen.