École polytechnique de Louvain (EPL)

Environmental and financial feasibility of a drone-built architectural structure

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Année académique 2015-2016
Master en ingénieur civil des constructions

ABSTRACT

Charles Coppieters de Gibson: Environmental and financial feasibility of a drone-built architectural structure.
(Under the direction of Pierre Latteur)

Digitalization is spreading across all sectors. The construction industry progresses with the development of Building Information Modelling (BIM), but the sector still lags behind. BIM has changed how construction projects are managed but does not revolutionize how they are built.

Recently, drones have been introduced in our lives. What if the drones were capable to build the homes of tomorrow? This study is motivated by keeping humans at the center of revolutions. The research has two goals: to quantify the environmental impact and the costs of drone-built architectural structures. Previous research has measured the environmental impact of single-family houses built by human workers as well as has detailed the construction costs. Our most significant contribution is the environmental and financial comparison between using human workers and drones. We conducted a life cycle assessment (LCA) on a Belgian single-family house. Contrary to our expectations, the analysis showed that drone-built walls and floors lower the house's climate change impact by 0,1 percent. Furthermore, using drones enables us to build twenty times faster for one third of the price.

ACKNOWLEDGEMENTS

I wish to thank all people who took part directly or indirectly to the realization of this thesis.

To Prof P. Latteur, École Polytechnique de Louvain (EPL), Université Catholique de Louvain (UCL), for the opportunity given to be part of the research team. For his trust and freedom in my choices even if he was there to assist me.

To Prof A. Funhoff, Managing Partner at Emerald Financial Advisers, for his precious time, his knowledge and expertise in entrepreneurial finance.

To my assistant, Mr S. Goessens, École Polytechnique de Louvain (EPL), Université Catholique de Louvain (UCL), for his guidance.

To Julie Gotal, Manager at Maisons Blaviers, for her time and data from the Manhay house.

To Dominique Pirlot, Head of Division at CSTC, for his help and introduction to the OptiCost research.

To Mr E. Coppieters, CEO at Caulier, for advice, encouragements and guidance to think one step further.

To Mr F. Joris, Altran consultant at GDF Suez, for his knowledge and expertise in Belgium's energy supply.

To Mr A. Pirson, Sia Partners, for his knowledge in renewable energies.

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List of Abbreviations

CAPEX – Capital Expenditure

CSTC – Centre Scientifique et Technique de la Construction

DCF – Discounted Cash Flow

EPL – Ecole Polytechnique de Louvain

EPP – Environmental product profile

FCF – Free Cash Flow

GCE – Génie Civil et Environmental

iMMC – Institute of Mechanics, Materials and Civil Engineering

KBOB – **K**oordinationskonferenz der **B**au- und Liegenschaftsorgane der **O**ffentlichen **B**auherren

(Conférence de coordination des services de la construction et des immeubles des maîtres d'ouvrage publics)

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

MIT – Massachusets Institute of Technology

PMP – Plate-forme Maison Passive

SPW – Service Publique de Wallonie

VAT – Value Added Tax

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1 Introduction

1.1 Research justification

1.1.1 Biomimicry in the design and build process

Rethinking the world of construction, is an idea which animates Pierre Latteur[1], professor at the École Polytechnique de Louvain (EPL). His vision is to supplement or even to replace manpower and construction cranes with drones. His inspiration has its origin in swallows that build nests by constantly making short trips to transport and assemble mud and twigs into a structure capable of supporting eggs and offspring. Other kinds of flying animals such as bees proceed in a similar fashion to construct complex structures (see Figure 1).

Figure 1 : Complex structures built by animals.[61] *Left: swallows building their nest. Right: A honeycomb*[62].

The feasibility of a biomimicry-based construction approach using unmanned aerial vehicles, commonly called drones, has already been investigated and validated by Jean-Sebastien Breton and Justin Leplat in their 2015 thesis written under the supervision of Professor Pierre Latteur at UCL. [1]

[1] Pierre Latteur is professor at the École Polytechnique de Louvain (EPL), affiliated with the Institute of Mechanics, Materials and Civil Engineering (iMMC) and the Civil and environmental engineering (GCE) division.

1.1.2 Similar works around the world

In 2011, researchers led by R. D'Andrea at ETH Zurich in association with the Swiss architecture firm Gramazio Kohler Architects, orchestrated a building project of rigid rectangular bricks through the use of drones. the final structure was a six meter tall tower composed of 1500 foam modules assembled by 4 quadcopters (see Figure 2) [2].

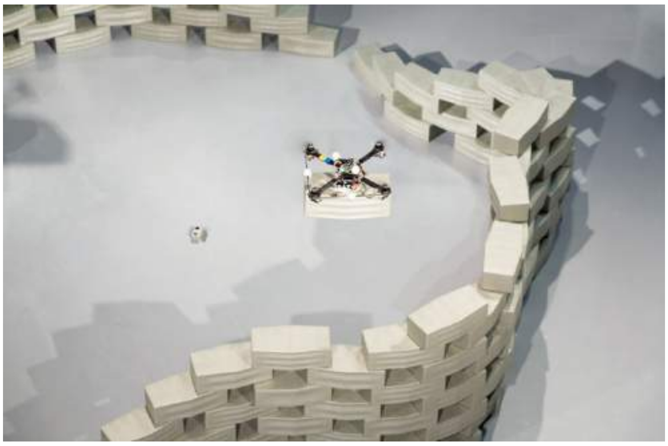

Figure 2 : Construction with bricks placed by drones (ETH Zurich/Prof R. D'Andrea).[63]

Professor R. D'Andrea's research group also investigated on how to "weave" simple tensile structures in the air with cable dispensers (see Figure 3) [3].

Figure 3 : Tensile structure made of cable (ETH Zurich).[64]

Finally, Quentin Lindsey, Daniel Mellinger, and Vijay Kumar from the University of Pennsylvania used teams of quadrotors to build tower-like cubic structures from modular parts assembled with magnets (see Figure 4). [4]

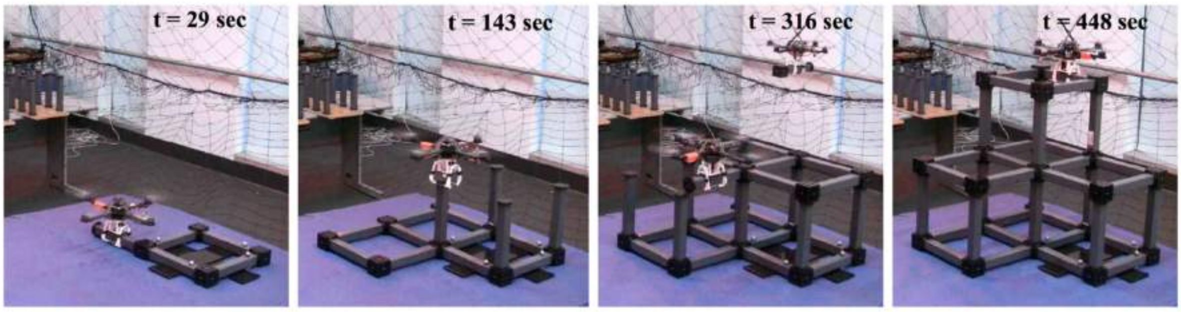

Figure 4 : Intermediate snapshots of a pyramid-like Special Cubic Structure being built by three quadrotors (University of Pennsylvania).[65]

1.1.3 Towards safer drones

New drone designs are trying to solve one of its major drawbacks: safety. Safer drones have already been designed. For safety, drones, such as "Fleye," now conceal propellers inside an outer shell. Fleye has the shape and weight of a soccer ball and it can be held safely as its single propeller is concealed within a sphere (see Figure 5(a)).[5]

The "Flying platform", a drone developed by Professor R. D'Andrea's research group, uses electric ducted fans as control and propulsion systems which, like Fleye, reduces the risk of injury (see Figure 5 (b)).[6]

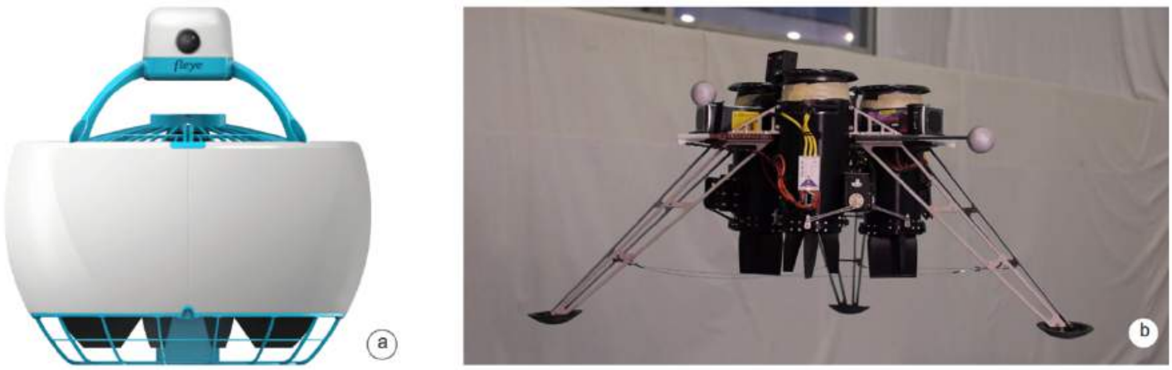

Figure 5 : New safer drone types.[5]

1.1.4 New designing mentality and brick types

While these developments are promising, investigation into additional structural units that can be used in drone-based construction, where less precision is available than with manual or other robotic methods, is essential.

During his PhD at UCL, Sebastien Goessens developed droxels (see Figure 6) which aim to be more drone-compatible than typical structural units. He explained, during his T.V. interview with RTBF's « Quel temps!» broadcasted on May 23rd, 2016, that droxels will likely not be the final and optimal form, as these structures will continue to evolve with time and research. New blocks will be engineered with more complex forms to inaugurate an era of drone-led construction that will be more efficient and safer.

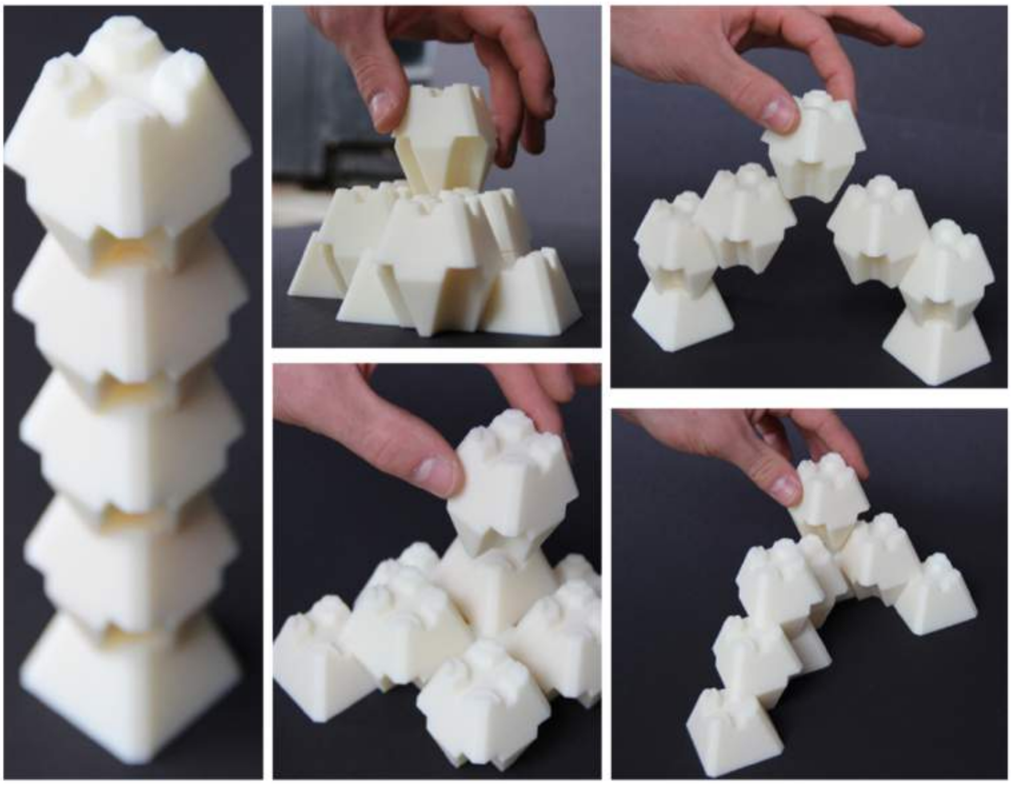

Figure 6 : Structural configurations assembled with 3D printed Droxels.

The use of drones in the construction sector will also require a significant mentality shift in the way buildings are conceived. According to Goessens, buildings will not only be created with new elements and techniques, but the architecture will likely explore new shapes and building types due to the forms of the new construction elements.

Drones provide interesting possibilities in the development of new construction methods. Indeed, drones are able to move around space and have access to places in a way men or a cranes cannot. Furthermore, the construction process could be safer, more flexible, faster and better coordinated with the use of drones. This applied research project in collaboration with Prof. Caitlin Mueller of Massachusetts Institute of Technology (MIT) aims to reduce the costs of defects caused by human and external factors, which can represent up to 10 percent of the total cost of a structure. While promoting the training of qualified personnel in a leading sector, drone reliance in construction will also increase on-site safety and will probably allow construction at a faster pace.

1.1.5 A revolution

In his conference "L'économie de la connaissance" the Professor and researcher Idris Aberkane states that:

"*Every revolution in the history of mankind that is scientific, cultural, political, moral, philosophical, technological or managerial goes inevitably through three steps:*

At first it is considered as ridiculous;
Then it is considered as dangerous;
And finally it is considered as obvious."[7]

Aberkane illustrates his point through the woman's right to vote. Two hundred years ago it would have seemed ridiculous that women could have a political opinion. Today, this right seems evident.

The drone revolution is just at its beginning and yet many applications have already been found for these flying robots. Drones are used not only for videography, mapping, disaster response, but also in the inspection of dam and bridge constructions, with the aim of identifying defects, leakages or cracks. Designs are evolving quickly and drones can lift more weight with each passing day.

1.2 Thesis purpose

1.2.1 Environmental impact

This research started in January 2016. One month after the COP21[2] was held in Paris. This event garnered worldwide attention because we are at the edge of a point-of-no-return. Following this conference, universal agreements will be signed. These engagements will be reviewed every five years. We can easily imagine that, in a near future, companies who contribute to climate change will be taxed and fined. Furthermore, companies with lower energy consumption are financially winning on the long run.[8] Many studies on the environmental impact and energy consumption have been conducted over the last decade. Life cycle assessments (LCA) in the construction sector mainly concentrate on two stages of a building's life cycle: production of its materials and the use phase. In a way, there is some sense in focusing on these two stages as they have a significantly high environmental impacts (see Figure 7). However, few studies have examined the construction stage even though it is essential to evaluate different construction techniques.

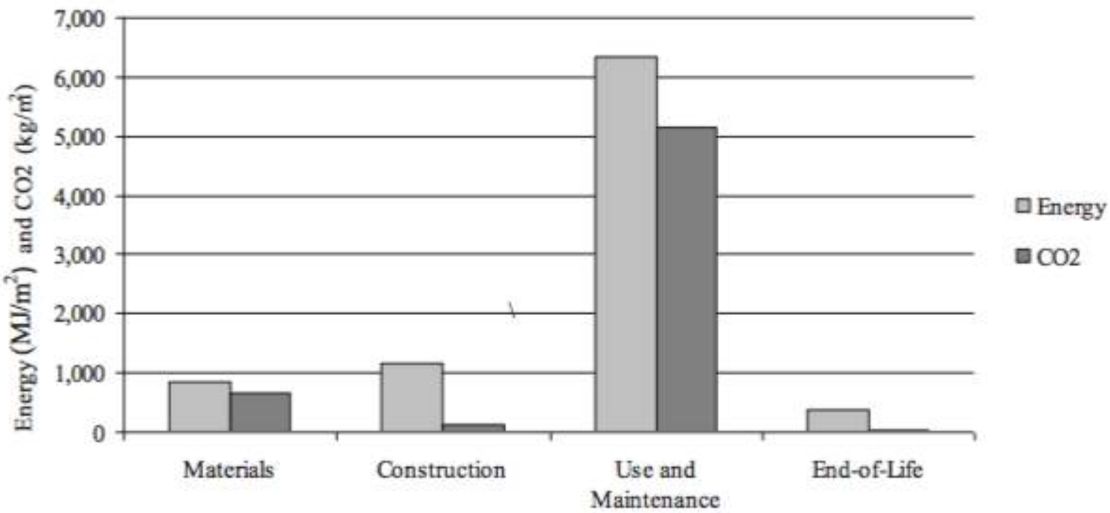

Figure 7 : Energy consumption and CO2 emission by life-cycle stage of a 17280 m^2 steel-framed office building.[66]

[2] COP21 - Conference of the parties (COP), is the 21st conference organized by the UN. This conference's oversees climate, and climate change.[60]

1.2.2 Financial feasibility

We live in a capitalistic society and discoveries don't have a future in the market if they are not profitable. Who will invest in the research and development needed to set up the project? At the moment, the idea of building with drones is perceived as ridiculous. Even if the technology existed, people believe it will be too expensive.

1.3 Thesis objectives

In conjuction to this work, Amaury Moncourrier and Adrien Naveau, fellow students at the École Polytechnique de Louvain (EPL), UCL, are developing new shapes of drone-compatible bricks (dricks) as well as a lifting system.

Nabil Nehri and Alexis Paques, students at ECAM, Brussels Engineering School, are developing an accurate positioning system for the drone so it can define its coordinates in a well-defined reference frame. They are adding a first layer of artificial intelligence to the drone.

Finally, Milan Reniers, student at EPL, UCL, developed elementary BIM tools for modeling a small size structure and translated the 3D model into drone-compatible remote control instructions.

This study focuses on single-family houses and more precise masonry and floors made of prefabricated elements. Moreover, the values used in this research are specific for Belgium. This thesis aims to make drone-based constructions possible by following two main objectives:

1. Environmental impact of a single-family house:

    The first chapter delves into the details of Life Cycle Assessments (LCA): what it does, its function, the methodology, the software etc. Then, two construction scenarios will be analyzed for a single-family house. The first example is a traditional human-built home. The second insistence will suppose that the walls and floors are drone-built. Finally, a comparison will be made between both scenarios.

2. Financial feasibility of a drone-built architectural structure:

    To prove that a drone-built architectural structure is financially advantageous, it has to be compared to the existing costs. Therefore, the first part details the different costs and prices related to the traditional construction of a standard single-family house. Then the costs of a drone-built wall and floor are examined. With the given information it is possible to compare and obtain a conclusion. Finally, a model evaluates the worth of a business building walls with drones.

2 Life Cycle Assessment

2.1 Introduction

The life cycle assessment (LCA)[3],officially named in 1991[9], is an globally accepted tool. It analyzes engineering designs (as well as processes and products) and finds ways to reduce humankind's environmental impact. The tool examines all processes of production, from the beginning to the end of the product's life[9] For instance, the life cycle of a building can be established through four stages : material production, construction, use phase and maintenance, and demolition. Sometimes a fifth stage is added and takes into account waste management.[10] The International standards of series ISO 14040 definition is the following : « LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle to grave) from raw material acquisition through production, use and disposal » [11] The study consists of exanimating the inflows and outflows of the product through the steps mentioned above. The inputs incorporate the elements needed to produce and transport the product while the outputs cover the emission and waste produced by the product during his life and at the end of his life. Such a system is represented in Figure 8.

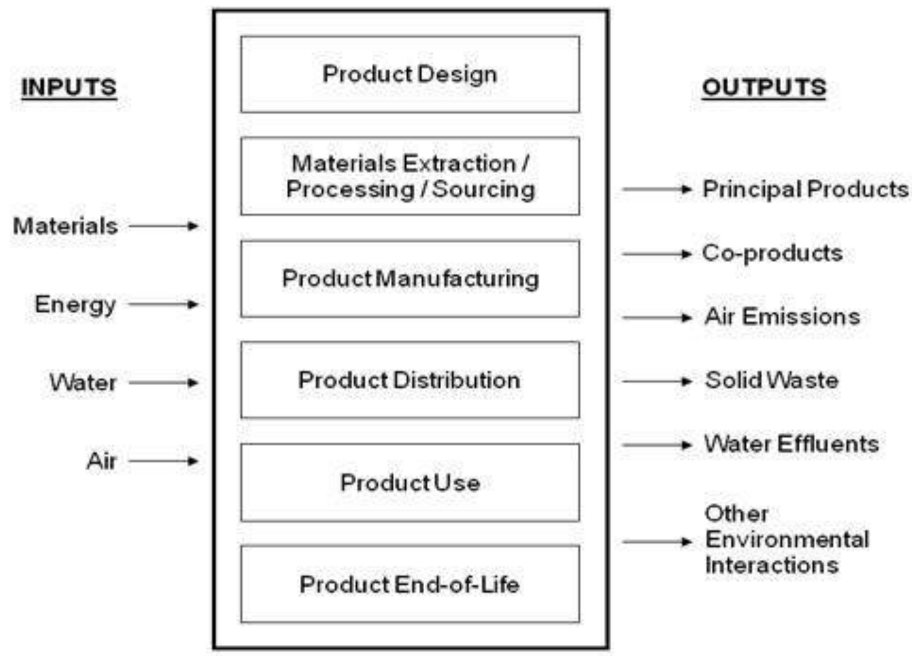

Figure 8 : Product system in a LC.[67]

[3] The life cycle of a product is the series of stages through which the product passes during its lifetime.

LCA is not the only existing method to measure the impact of a design. Various environmental studies have been executed with techniques such as the Environmental product Profile (EPP) and "ecobalances"[9]. These methods merged to form the LCA. Today's different methods have different goals and are used for different purposes. However, the LCA remains the most popular as it is the most thorough and comprehensive tool. It enables the user to get overview of different aspects of a product's environmental impact, not only its material inputs.

A LCA can focus on one particular flow of the product, like the energy consumption or its emission. This will depend on the objective of the study and which type of LCA is executed. ISO 14040 mentions two different approaches:

- The attributional type develops a global view of the environmental impact of a specific product. Such an approach can identify the areas of the life cycle with the greatest impact.

- Consequential LCAs analyze different products to identify the best solution to lowering the environmental impact. This type can also be used for eco-labelling to help the consumer in his choice.[12]

Who carries out the LCA? Various entities can be motivated to pursue such a study including private researchers, industries, and even governments. Architects and engineers tend to start a LCA to explore decisions for each life stage of a product.[13] LCA results vary depending on the boundaries defined by the researcher. Therefore, comparing different LCAs of a same product can lead to inappropriate conclusions.

2.2 Methodology

ISO 14040 defines the LCA as a methodology which consists of an iterative four-step process.

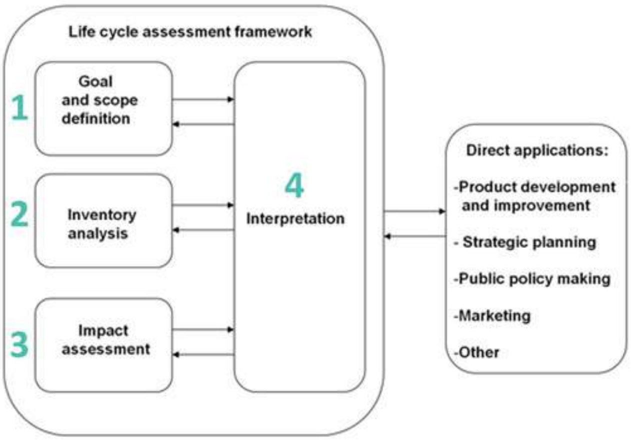

Figure 9 : Steps of an LCA defined by ISO 14040.[68]

2.2.1 Goal, scope and definition

This section is dedicated to define boundaries. It covers why the study is being performed as well as a description of who is executing it and to whom the results will be communicated. Whether the study focuses on a product, an element, or a building, there are various parameters. For construction products, European norms (NBN EN 15804), defines three boundaries:

- Cradle to gate only takes into account the production. It's only a partial study of a product's life cycle (i.e., the extraction of raw materials to the factory). One of the significant uses of this scope is to help achieve a cradle to grave study.

- Cradle to grave takes into consideration all the different stages in the product's life cycle. The study covers all the inflows and outflows at each stage.

- Cradle to cradle is a closed loop. At the end-of-life, the product is recycled to make another product (i.e., collected glass bottles that are melted into new bottles).

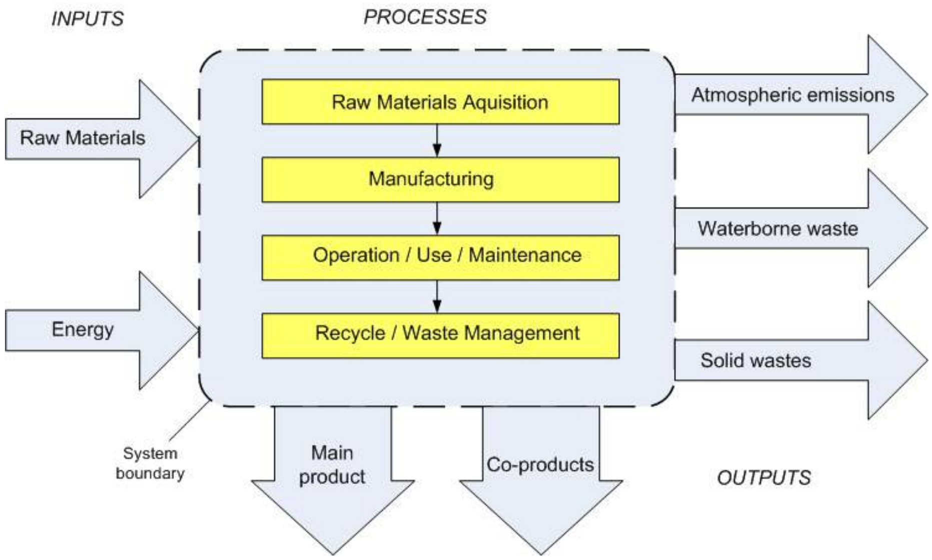

Figure 10 : Different phases of an LCA in construction.[69]

The functional unit has to figure somewhere in this section. "The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related."[14] This unit enables the comparison between different studies. I.e., the functional unit of a paint system could be defined as the surface recovered for 9 years. With the same functional unit, the environmental impact of two paint system could be analyzed.

The life time of the product, element or building has to be determined. A life span of sixty years is generally allocated to buildings [15]. If components have lower life spans, their replacement will be taken into account during the evaluation.

Eventually, the methodology used is described such as the various criteria for eligible data and their possible sources, as well as the software used to conduct the assessment. Section 2.3 covers some popular software's.

Finally, a series of criteria used to assess the environmental impact are explained. Each LCA have to use all the indicators suggested by the European norms. The analysis can select the ones relative to its particular goal. The different indicators are developed below, in section 2.2.3.

2.2.2 Life Cycle Inventory

The second step of an LCA is the Life Cycle Inventory (LCI). This step consists of assembling the necessary data to develop the analysis.

In Figure 10, the system is divided by a series of processes. For each process, the inflows (i.e., energy, raw materials etc.) and outflows (i.e., emissions, landscape changes etc.) are inventoried quantitatively and qualitatively. For example, the transport from the factory to the construction site takes into account the transport type, the distance and the weight carried. Then, the quantity of each inflows and outflows is linked using the functional unit.

The difficulty in this step is mainly due to the repartition of the environmental impact between the different products coming from the same process (i.e., the environmental impact of life stock has to be divided between the different sources, meat and wool). How this division is made is important as it can greatly influence the results. Moreover, this problem is also present when a product is reused or recycled. The negative impact (reduction of energy) and positive impact (energy consumption or waste created during the process) due to recycling or reuse has to be taken into account by both LCA of the product that is at its end of life and the LCA of the new product benefiting from the old product.

2.2.3 Life Cycle Impact Assessment

Once the inventory step of the global assessment is completed, the impact assessment can be crafted. This step quantifies the potential environmental contribution of a product on different impact categories. Impact categories, such as climate change, acidification, are important themes in today's society. These impacts are due to emissions in the air, soil, and water or to the use of certain resources (i.e., water and fossil fuels). These impact categories can be assessed with the help of environmental indicators. As already stated, the choice of the studied indicators will depend on the objectives of the LCA. Table 1 is a summary of various environmental indicators suggested by the European norms NBN EN 15804 and NBN EN 15978.

The inputs and outputs collected during the LCI are now regrouped and assigned to each selected indicator. For example, while CO_2 contributes to climate change, NO_x will be assigned to acidification and eutrophication. As mentioned previously, the contribution of each inflow and outflow is expressed in a functional unit (i.e., kilograms of CO_2 equivalent for climate change. One kilogram of CH_4 is equivalent to 25kg of CO_2).

Table 1 : Various environmental indicators.[30]

Impact category		Unit	Description
CC	**Climate change**	kg CO_2 eq	To air, global. Emissions who contributes to the greenhouse effect by increased infra-red radiative forcing in the atmosphere.
HT	**Human toxicity**	kg 1,4-DB eq	To urban air, site-sensitive. Effect of toxic substances to human environment. Air emissions of heavy metals are specifically large contributors
POF	**Photochemical oxidant formation**	kg NMVOC	To air, site-sensitive. Formation of ground-level ozone, indicated as "summer smog". "Ozone is a health hazard to humans because it can inflame airways and damage lungs" (Goedkoop et al., 2009).
PMF	**Particulate matter formation**	kg PM_{10} eq	To air, regional air quality. Particles in the air generated by mainly combustion of fossil fuels. Causes health problems for airways and lungs.
TA	**Terrestrial acidification**	kg SO_2 eq	To air, site-sensitive. Inorganic gases (sulfates, nitrates and phosphates) may dissolve in water and change acidity in, e.g., soil and groundwater. Acid rain.
FE ME	**Freshwater eutrophication** **Marine eutrophication**	kg P eq Kg N eq	Both to freshwater, site-sensitive. Nutrient-rich compounds released into water bodies. Can cause algal bloom which may lead to an adverse ecological effect.
TET	**Terrestrial ecotoxicity**	kg 1,4-DB eq	To industrial soil, site-sensitive. Risks of damage to ecosystems on land by emissions of toxic substances.
FET	**Freshwater ecotoxicity**	kg 1,4-DB eq	To freshwater, site-sensitive. Risks of damage to freshwater bodies, as a result of emissions of toxic substances to air, water and soil.
MET	**Marine ecotoxicity**	Kg 1,4-DB eq	To marine water, site-sensitive. Risks of damage to marine ecosystems by emissions of toxic substances.
MD	**Metal depletion**	kg Fe eq	The depletion of metals and minerals can be described as the decrease of available reserve of minerals due to extraction and use.
CED	**Cumulative energy demand**	GJ eq	Accumulated total primary energy required, fossil and renewable.

2.2.4 Interpretation

The objectives defined in step one can now be answered. However, new questions often arise during this stage as the results have to be discussed and interpreted by the concerned parties. This discussion usually proceeds in three steps: the identification of significant factors, the verification that the latter is complete and coherent, a conclusion and recommendations for future analysis.

2.3 LCA Tools

Environmental policies are increasingly dominating global discourse so that, in recent years, life cycle analysis has become a pivotal aspect to discussing the issues at hand. In response to this new trend, many tools, which have an important impact on the efficiency of analysis, have been developed. Although the theory remains the same throughout the new tools, the framework, the functions, and applications can vary greatly. According to a 2006 study on 60 LCA practitioners, of the four LCA tools studied, GaBi and SimaPro were the most popular[16].

2.3.1 Software

BEES 4.0

Building for Environmental and Economic Sustainability (BEES), is a free tool which breaks down the costs as well as the environmental impact. It was developed by National Institute of Standards and Technology (NIST) and enables users to select building products with a cost-effective analysis. The targeted users are builders, designers, and product manufacturers. The life cycle of a product is fully studied. The tool has twelve indicators for the environmental impact and two for the financial aspect (see Figure 11 : BEES model).[17]

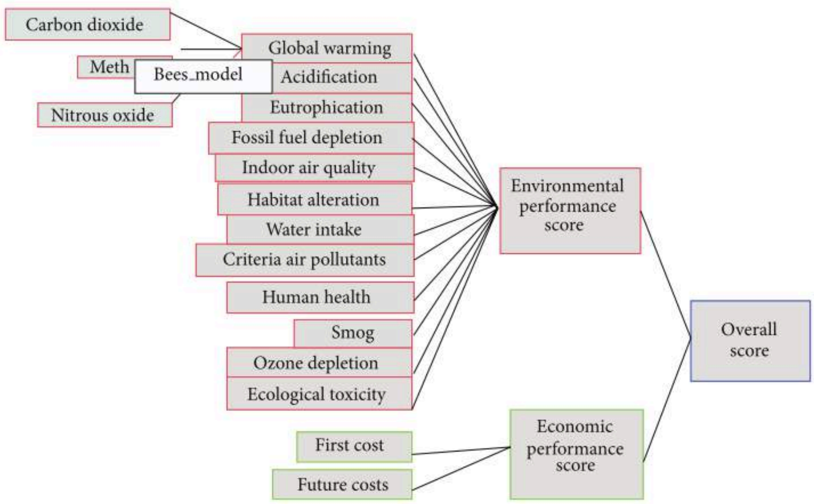

Figure 11 : BEES model.[17]

Athena Impact Estimator

This tool is also free but unlike BEES, it can be run on mac computers through an emulator. The targeted users of this tool are architects, engineers, and researchers as it enables them to make comparisons between various designs. Its main use is for the conceptual stage of a project.[13]

SimaPro

SimaPro, a leading tool, is used worldwide. However, it is not free. Its fame comes from the database. It enables users to have a lot of flexibility (i.e., it is possible to make links with outside data sources). Customers can extend and change the data to according to their needs. It is a professional tool for products and services which adapt easily to a wide variety of situations.[18]

GaBi

GaBi is also a leading software. It is made for more experienced users who wish to delve further into technical details. Customers have to build the lifecycle of a product with an engineering approach. The tool offers a highly reliable and flexible database, parameter variation and scenario analysis.[19]

BeGlobal

This Belgian project started in 2012 with the help of Plate-forme Maison Passive (PMP). This non-profit's objective is to inform architects and engineers on a building's environmental impact in order to optimize the latter. Its website is user friendly and makes the analysis process an easy task. However, sufficient information on the use phase of the building is necessary to carry out the analysis. Furthermore, the construction phase does not take into account the energy consumption of the construction equipment. Its library is small and specifically designed for Belgium.

2.3.2 Comparison

Table 2 shows the difference between the four tools. As was explained, they vary in terms of performance and application. However, they all lack data and precision of the construction phase.

Table 2 : Comparison results. [20]

Tools	Country	Developer	Main functions	Database extensibility	Application range
BEES	America	National Institute of Standards and Technology	1. Life cycle costing assessment 2. Life cycle impact assessment	Fixed	Building
Athena Impact Estimator	Canada	Athena Sustainable Materials Institute	1. Life cycle impact assessment	Fixed	Building
SimaPro	Netherlands	Pré Consultants B.V.	1. Life cycle impact assessment 2. Database Management	Flexible	All industries
Gabi	Germany	PE International GmbH	1. Life cycle impact assessment 2. Database management	Flexible	All industries
BeGlobal	Belgium	Plate-forme Maison Passive	1. Life cycle impact assessment	Fixed	Building

3 Environmental impact of a single-family house

In this chapter we will assess the impact of a house on climate change and energy consumption. The first LCA will assess a house built by humans. The second will consider the intervention of drones for the construction of the walls and floors.

The LCA was done through the program BeGlobal, a free web site put online by Plate-forme Maison Passive (PMP). We have chosen this software for its ease of use and specific usage for houses. Furthermore, it was suggested by Geoffroy Bekkers, head of the department "Construction Durable" at Besix. Aside from being free, it executes the analysis without superfluous technical details, unlike SimaPro. The website provides all the data required to assess the materials. However, as mentioned in section 2.2, the platform does not analyze the impact of construction in-depth. The latter will have to be done in addition and added to the results.

This study has two main goals. The first one is to assess the difference between the environmental impact of a traditionally built house and the environmental impact of a drone built house. Second, we would like to quantify the importance of this difference by comparing the different phases of the house's life cycle.

3.1 Human built house

3.1.1 System description

In this section the environment of the study, such as the location and plans of the building, is developed, the functional unit is defined, and the limitations of the study are explored. The weather is not assessed as it is not necessary for the study as the weather forecast is already taken into account by the Performance Energétique des Bâtiments (PEB) certificate.[21]

3.1.1.1 The house

The house studied is being built by Maisons Blaviers. The house is located in Manhay, Wallonia, 65 kilometers south of Liege. It is a concrete based two-floor single-family house with 192m^2 of heated floor and a perimeter of 40 meters. It is built to accommodate five people. Figure 12 shows the façades which have 9 windows, 4 French windows and one outer door. The technical drawings can be found in Figure 13. Confer. Annex 1 for more plan details.

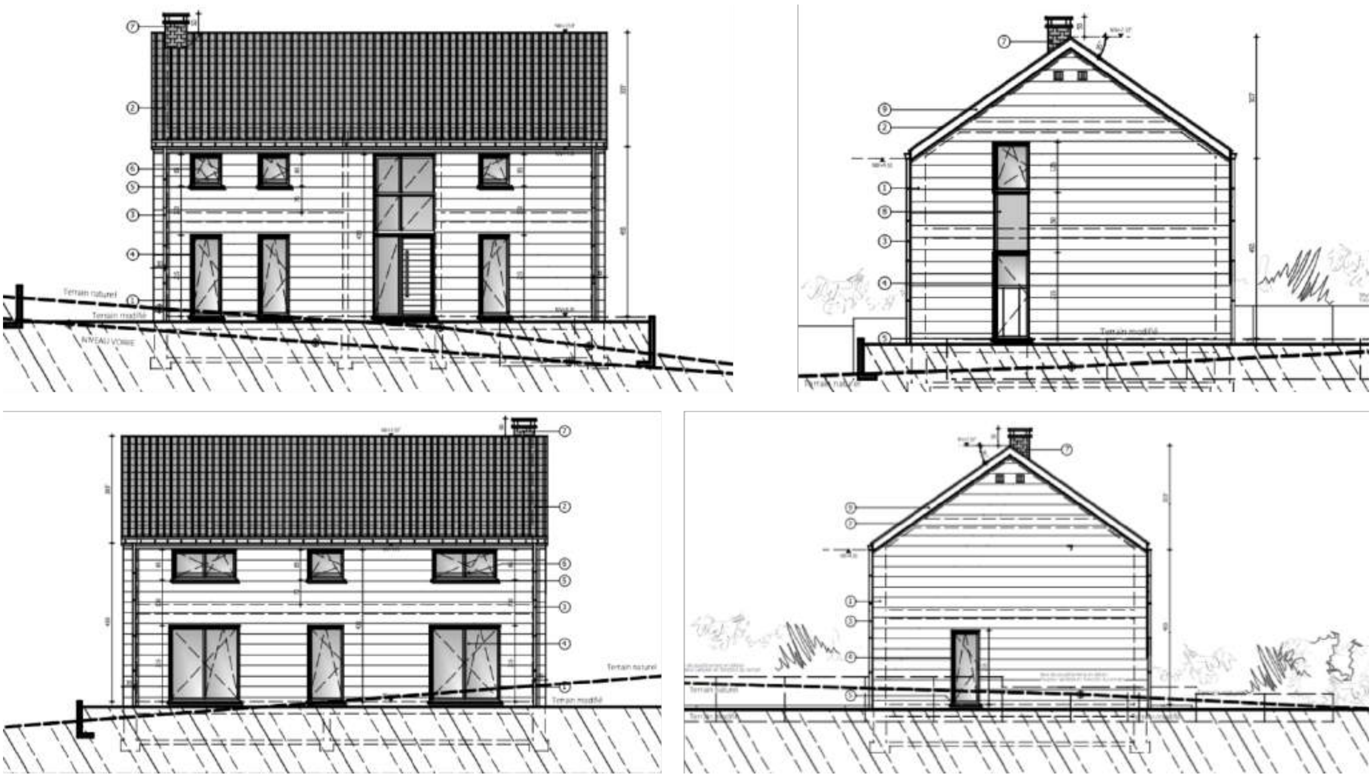

Figure 12 : Front, right, back and left view of the Manhay house.[70]

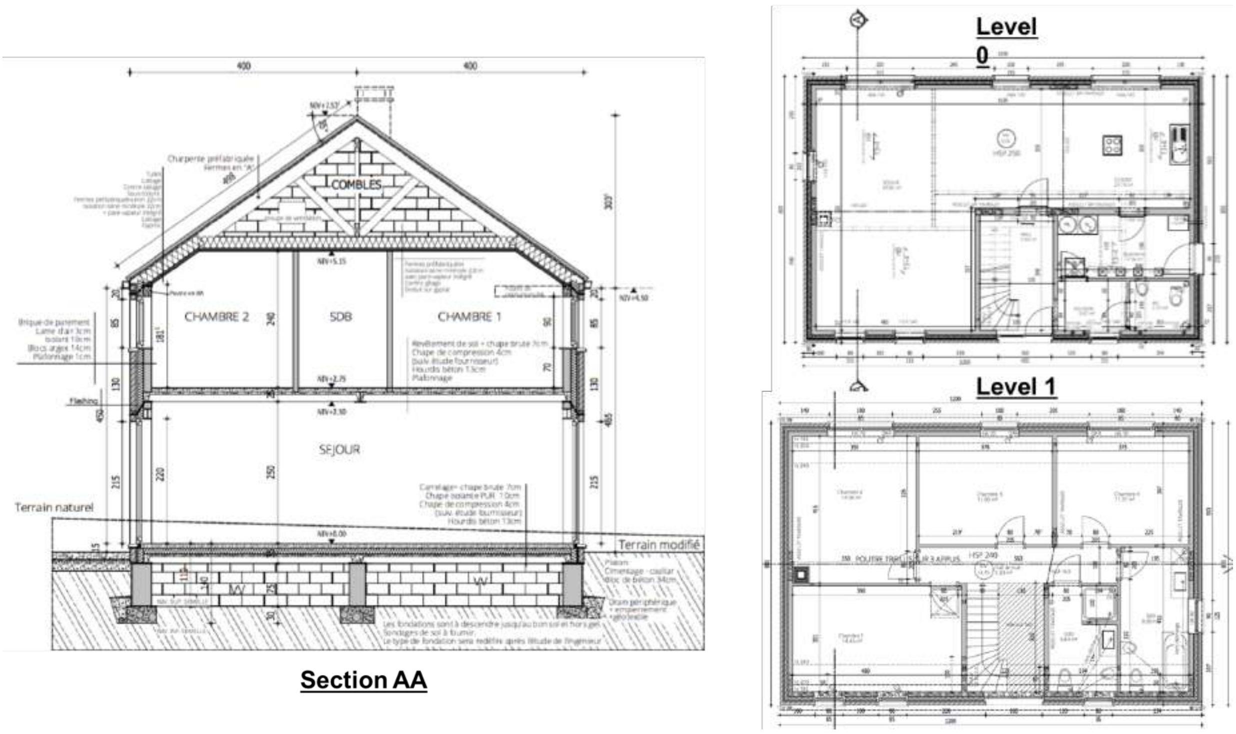

Figure 13 : Technical drawing of the Manhay house.[70]

Functional Unit

The lifetime of a house is a hard parameter to define. To this day, no norms exists on the lifetime of a material.[22] In the literature we find lifespans varying from 25 to a 100 years. Ghattas et al., analyzed 66 individual building cases and demonstrated that a long lifespan increases the dominancy of the use phase's energy impact. Most of the studies use a lifespan of around 50 years.[23] Studies with determined lifetimes of a 100 years take into account a higher amount of renovation activities.[24] In our case study, we have chosen 60 years, as is recommended by the CSTC.[15] Though PMP suggests a lifetime of 80 years for a residential building, 60 years is consistent with the objectives of high GHG reduction in the years to come. Legislation on the energy consumption during the use phase is due to change greatly and it would not be pertinent to use a long lifetime. [25]

The functional unit of the LCA is the following:

"1 m^2 of heated floor area of a residential house, including the whole building life cycle (construction, maintenance, operational energy, and end of life treatment), considering 60 years as the lifetime of the house."

The environmental impact will be assessed by the energy consumption and GHG emissions (which is expressed in kilogram equivalent of CO_2). The global energy consumption of the building is the sum of the grey energy[4] of each material and the primary energy consumption during its lifetime (such as heating, cooling, electricity and domestic hot water). These indicators are the most reliable since drones will require a change in tools, but not materials to build the house. Furthermore, the tools have a greater impact on the energy consumption than metal depletion, marine ecotoxicity, terrestrial acidification etc.

System boundaries

To achieve our goals, we chose a cradle-to-grave system. This will enable us to have an overview of each step of the life cycle while being able to compare the two construction phases. Figure 14 illustrates this system for the functional unit. In dark blue are the four main parts of the system.

- The material production takes into account all the materials used to build the structure of the house. This does not, however, take into account the wiring, piping and ventilation systems. The environmental impact of this phase is the combination

[4] «Grey energy is the hidden energy associated with a product, meaning the total energy consumed throughout the product's life cycle from its production to its disposal »[61]

of all the processes before the final product leaves the factory for the construction site (i.e., the extraction of raw materials is integrated into the total).

- The house construction phase includes the transport of the materials from the factory to the construction site, as well as the equipment used and the workers' travel. On-site, the machines, which combust diesel (such as the cranes), are integrated in the analysis. Other tools, with electrical energy consumption, for example, are also taken into account.

- Finally, after sixty years, the house is dismantled, the materials are treated as waste, and they are brought to a nearby landfill. The impact depends on the equipment used and the distance to the landfill.

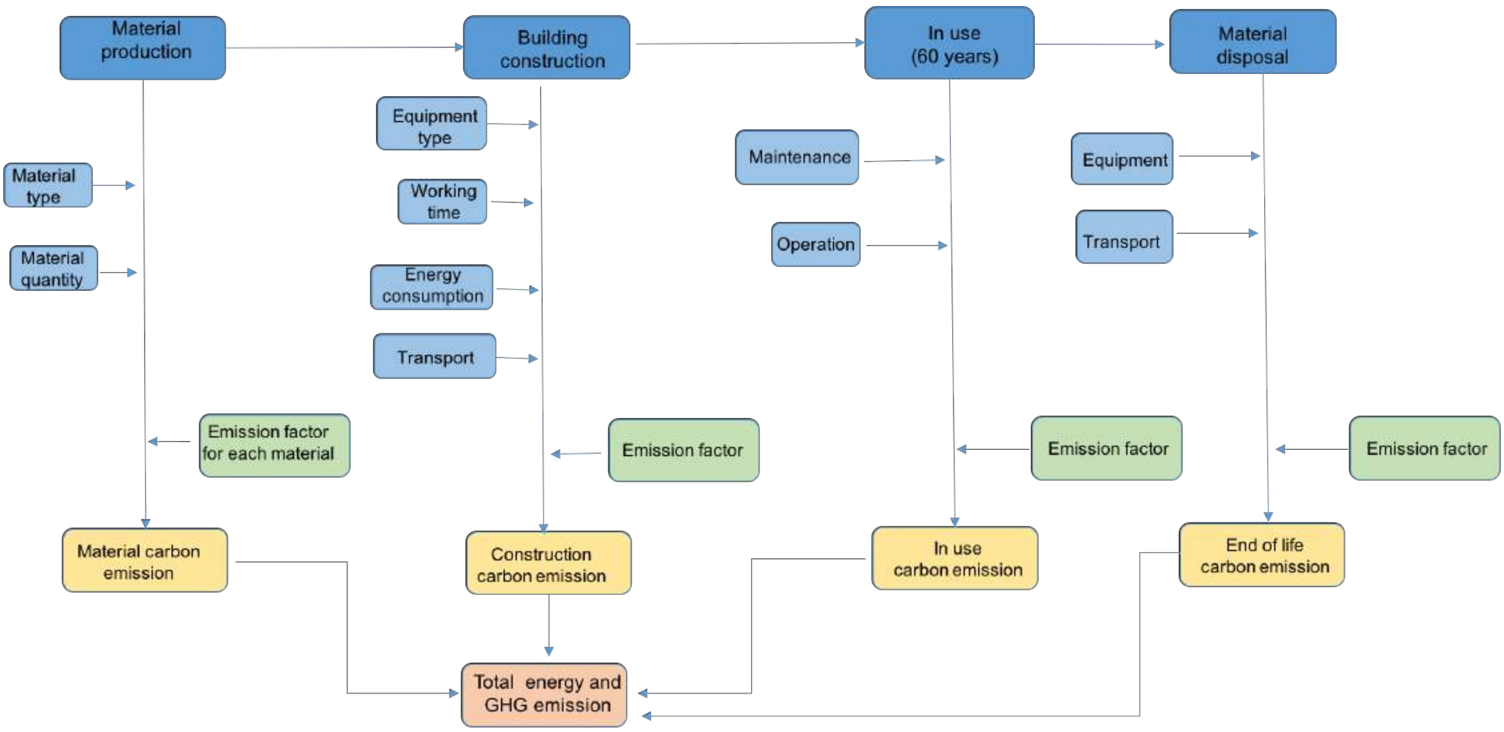

Figure 14 : Flow chart of the Manhay house

3.1.2 Life Cycle Inventory Analysis

This section elaborates on the data used per to the flow chart previously examined. They are all transformed to the functional units so that the data can be compared among themselves and then assessed for the overall impact. Unless otherwise mentioned, the data collected comes from the KBOB database, provided by PMP. This assures the quality and consistency of the data used. The LCI is divided into three parts: house in construction, in-use and end of life.

House in construction

This part includes all the operations to build a house, from the untouched land plot to the complete house. The material list was provided by Maisons Blaviers and is further developed in the following sequence: walls, roofing, foundations, floors and ceilings, doors, windows, building structure, and construction energy. The civil engineering bill can be found in Annex 2.

Walls

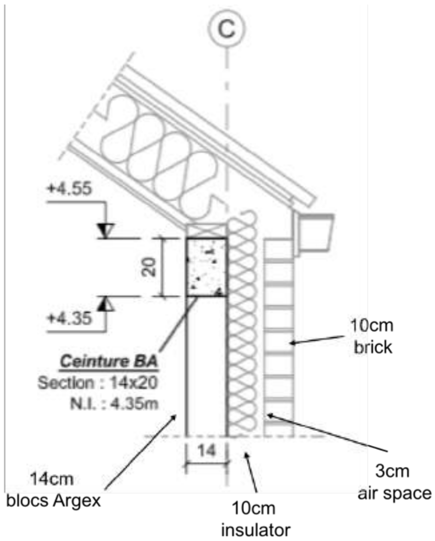

Figure 15 : Outer wall detail of the house.[70]

The house has one type of outer wall and three different inner walls. The materials are supposed to be produced in Belgium. The outer wall is 37 centimeters thick. Figure 15 illustrates the five layers which make up the outer wall. The heat transmission value U (equal to $0{,}23\,\frac{W}{K.m^2}$) is lower than $0.66\frac{W}{K.m^2}$, the legal maximum value.[26]

The inner walls are 2,5 meters high on the ground floor and 2,4m on the first floor. They are either 19, 14 or 9 centimeters thick. The brick and Argex bloc layer will later be built by drones.

Roof

The materials are also supposed to be produced in Belgium. The interesting material here is the wooden batten. The CO_2 emission during the production phase (of the latter) is negative due to the carbon stocked in the wood.[27] Figure 16 illustrates the different layers of the roof, which has a slope of 35°.

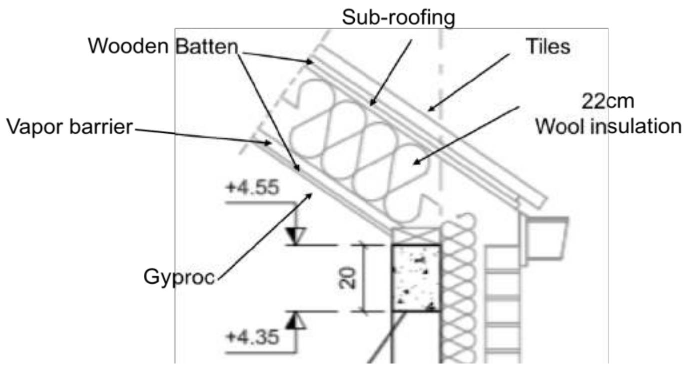

Figure 16 : Detail of the roof.[70]

It would be plausible to make a roof drone-constructible in a near future. However, with the lack of information and research on this subject, it will not be integrated into this work.

Foundations

The house is lain on a slope so the land had to be flattened. The groundwork estimates that 185m^3 of earth needs to be displaced. There are strip foundations which are then set 140 centimeters below the level 0. They are manufactured on-site and made of reinforced concrete C25/30. The hole is dug by hand and a concrete pump is ordered to fill it up. The foundation walls are 60 centimeters high, 34 centimeters thick, and made of concrete blocks.

Floors and ceilings

The floors are made of 13 centimeters thick hourdis which are presumed to have been made in Belgium. This structure has a potential to be drone-compatible. This possibility will be studied later on. A truck crane has to come twice on-site to deliver and place the elements. The first time for the foundation floor and the second time for the first floor.

Doors and windows

Both doors and windows have a heat transmission value under the legal maximum. There are 10 doors inside the house made of medium density fiberboard (MDF). The windows are elements which can impact the use phase of the house significantly. They can be a serious source of heat loss. Fortunately, the PEB has strict regulations concerning windows ($U_{max} = 1{,}8 \frac{W}{m^2.K}$). There are 14 windows and the thermic transmission value (U) varies between 1,43 $\frac{W}{m^2.K}$ and 1,55 $\frac{W}{m^2.K}$.

Building structure

The building structure is composed of wood. It is pre-made and installed by Chimsco. The impact is calculated from the weight of the structure. For such a framework (Fermes en “A”), the weight is 60kg per 60cm, which leads to an overall weight of 1480kg.[28]

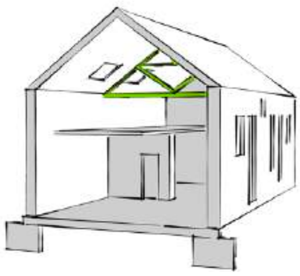

Figure 17 : In green, the wooden framework.[70]

Construction energy

The construction energy is essentially composed of the machines and tools used on-site. We have integrated another important factor which is the transport of the equipment and workers. We have based our assumptions on existing statistics so these values could be used on a similar house, located elsewhere.

Machines

The groundwork was estimated to be 185m^3. In order to accomplish the work, a 8 tons digger is employed. According to Eric Roebben, CEO of the Roebben company since 1970,[29] this type of digger has a bucket of 1,5m^3 and takes several seconds per buckets. With this information we made the assumption that it takes 35 seconds per bucket. Mr. Roebben approved a fuel consumption of 30 L/h. The machine is brought on-site by truck and the distance traveled by the truck is estimated to be 90km.[22]

A concrete pump has to come on-site three times, for the foundations and each of the two floors. It is assumed that the pump has to travel 90km.[22]

The hourdis are installed with the help of a truck crane. Maisons Blaviers evaluates the time of this manipulation to be four hours per floor. The truck consumes 20 liters of gasoline per day. The distance from the factory to the construction site is estimated to be 90km.

Various tools such as an air compressor, saw, lights etc. are assumed to use 2,8 kWh combined and to be employed 50 percent of the working time.[30] The emission factor for Belgium's electricity is elaborated in section 3.1.3 Electricity mix assumption.

Transport

It is assumed that each day two cars drive up to the construction site. The Service Public Fédéral Mobilité et Transport published a study in 2014 demonstrating that the mean distance for a Walloon working in Brussels was 44,3km.[31] For the rest of the study, this is the distance used for the workers' travel from home to work. It is forecast that such a house is built in 133 days. This includes the 15 days of masonry work and the two days for the floors.

What is not included

Anything that was not mentioned above is not taken into the house construction. For example, the study does not include the cladding, staircase, electricity work, nail and glue etc. Nevertheless, their energy consumption is incorporated into the use phase (i.e., heating and ventilation).

In – Use

Since May 2010 the analysis of the energy performance of a building is legally required for new constructions in all EU member states.[32] Therefore, Maisons Blaviers presented their report in November 2015 before the construction could start. The study was done through the PEB software provided by Service Public de Wallonie (SPW). The outcomes of this study are the following[26]:

- E_{spec} [5]= 123,5 kWh/m^2.an
- CO_2 emission = 21,5 kgEqCO_2/(m^2.an)

The maintenance of the house is defined by the lifetime of each product and is managed by the PMP platform. For example, the polyurethane insulation has a lifetime of thirty years. Therefore, it will have to be replaced once during the sixty-year lifetime of the house.

Deconstruction

In this study we have assumed that everything is waste and cannot be reused. The value given by PMP includes the incineration, landfill access and transport.

The demolition energy can be deduced from the time needed. Maisons Blaviers expects 50 hours of manual work and the use of an excavator for 25 hours. The excavator's consumption is 20 liters per hour and the workers ride 45km from their home to the site. The waste is then transported by a lorry, 3,5-16t, to a garbage dump and this distance is, by default, 30km.

3.1.3 Electricity mix assumption

Belgium's main source for electricity supply is the nuclear, with 44 percent its energy coming from nuclear power in 2014. However, it is very hard to predict if the distribution shown in Figure 18 will be the same in the future. The population's thoughts and E.U. legislations are changing each year. The Doel's reactors are constantly being turned on and off which can explain the high use of gas plants. Given such unpredictable future, we will not use forecasted distributions.

[5] « The specific primary energy consumption, E_{spec}, is calculated by PEB unit. It is expressed in kWh/m^2.yr or in MJ/m^2.yr. This is the ratio of annual primary energy consumption of a PEB unit and the total heated floor area of this unit. » [60]

Power supply, 2014

Type	Capacity (GW)	Production (TWh)	Share of production
Nuclear	3.9	29.5	44%
Gas	5.5	20.4	30%
Solar	3.0	2.2	3%
Coal	1.7	4.3	6%
Wind	1.8	4.7	7%
Hydro	1.4	1.6	2%
Other	1.2	4.6	7%
Oil	0.8	0.3	0%
Total	**19.2**	**67.7**	**100%**

Note: TWh = terawatt-hours.

Figure 18 : Distribution of Belgium's power supply in 2014
Source : IHS Energy [71]

Once the distribution is known, we need the carbon emission factor for each source in order to calculate the weighted average. CO2 emissions per kWh from electricity generation using:

- Coal: 1000 - 1300 kWh/CO_2.
- Gas: 330-360 kWh/CO_2.
- Nuclear: 90-140 kWh/CO_2.
- Solar, wind or water power: 10-40 kWh/CO_2.

The values above include the whole life-cycle of the power plant. This can explain why renewable resources emit CO_2.[33] [34]

The International Energy Agency (IEA) keeps annual statistics on the Organization for Economic Cooperation and Development (OECD) energy consumption. IEA evaluated Belgium's carbon emission factor to be 220 g per kWh from electricity generation in 2010.[35] As it is their latest value released, the 2010 value will be used for the rest of the study.

3.1.4 Life Cycle Impact Assessment

This chapter will assess the environmental impact of the Manhay house. A general overview of the life cycle will be explored and then the outcome will be analyzed. The results presented are per functional unit, which, as a reminder, is defined as the following:

“1 m^2 of heated floor area of a residential house, including the whole building life cycle (construction, maintenance, operational energy, and end of life treatment), considering 60 years as the lifetime of the house.”

The total climate change impact of the material production, transport, construction, maintenance, operating and demolishing is 414 tons of CO_2 equivalent, which represents an impact of 2,156 tons eq of CO_2 per meter-square of heated floor. The value of the emissions and energy consumption for each phase can be found in Table 3.

Table 3 : Energy consumption and CO2 eq emission during the human built Manhay house life cycyle

	Energy [kWh/m^2]	GHG emission [KgEqC0$_2$/m^2]
Material production	4678,8	624,6
Construction process	625,62	135,47
In use	7410	1290
End of life	315,6	103,2

These results are not surprising and are consistent with the literature. The use phase has the largest impact at 60 percent, followed by the material production, the construction process and finally the demolition process. Figure 19 is a visual representation of the breakdown with the impact percentage of each phase. Even if the impact of the house in operation was not taken into account, the construction phase would have a minority weight of 16 percent. In the next chapter we will see how this small value can be impacted by the introduction of drones.

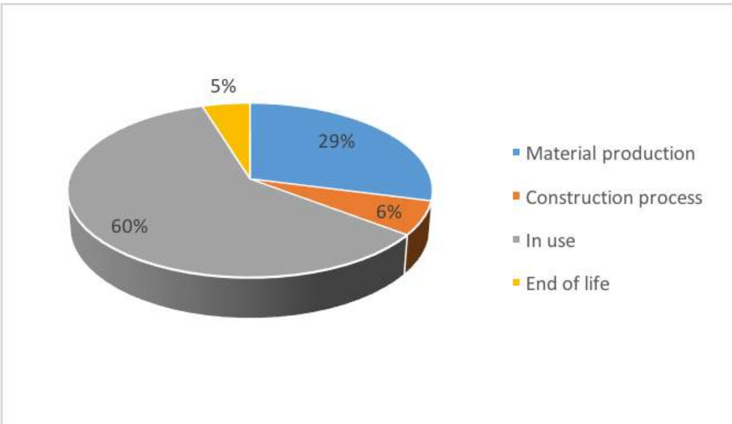

Figure 19 : CO_2 emission break down between the different phases of the human-built house.

3.2 Drone built architectural structure

In section 3.1 we mentioned the existing potential feasibility of a drone-built wall and floor. Other elements of a house will be drone-built in the future. However, these two elements (walls and flooring) will be on the market sooner and our research team has been working on them on those aspects particularly.

In order to keep the focus on the drones and elaborate a good comparison we have taken the following hypothesis:

- The materials and process used to make the bricks are the same.
  - They have the same properties (insulation etc.)
  - They have an equal lifetime.
- The end of life process is equivalent.
- Only one drone is working at a time.

With this in mind, the difference between the drone and human built house lies in the construction phase. As a result, we will have to add the energy consumption of the drones as well as the technician's travel. Accordingly, we will subtract the workers' travel as well as the machines used for the human built walls and floors.

3.2.1 Drone's properties

The drone used by the 2016 team, shown in Figure 20, was manufactured in Belgium by RC Take Off [36]. It has the power to lift a mass of eighty kilograms. However, for safety measures, the maximum load is set at forty kilograms (the user has to consider the batteries' and gripper's weight).

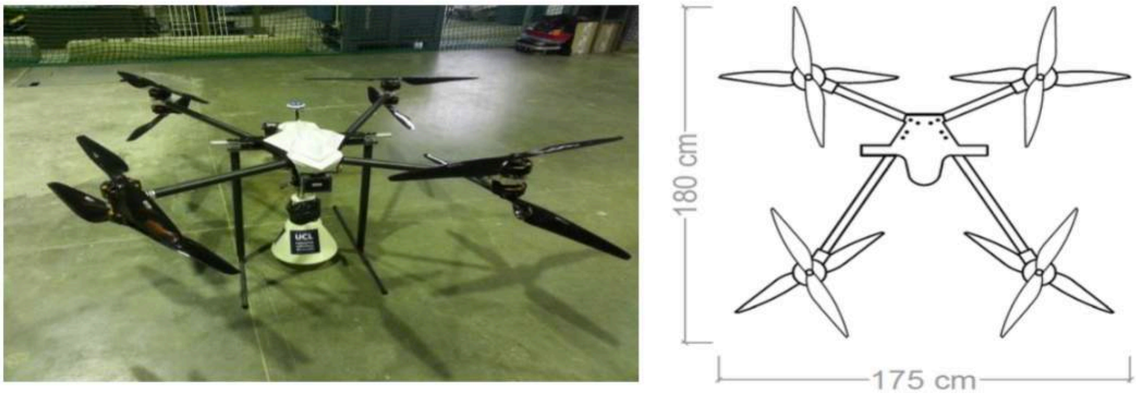

Figure 20 : Drone used by the 2015-2016 team.[72]

The battery is a key component of our study. Presently, the drone is powered by two 6s Lipo 22V/22ah batteries. Sebastien Goessens tested the batteries in March 2016 and evaluated the drone's consumption to be:

- 1kWh per hour of flight without any load.
- 1kWh per 20 minutes' flight with a load of 25kg.

In reality, the autonomy of a drone will vary significantly depending on the load and temperature.

We assumed that a drone needs 35 seconds to take a structural element from the pile, install it and come back to its original place. During these 35 seconds, the drone is loaded for 25 seconds.

3.2.2 Walls

Adrien Naveau and Amaury Moncourrier have been developing the optimal concrete block (40x15x20cm) for a drone-built wall. They studied the design as well as the composition.[37] The squared-pyramids illustrated in Figure 21, enable the blocks to stack properly within a five centimeter precision range. The block's composition is detailed in Table 4. This composition was established as the best for its ease of use.

Table 4 : Concrete composition of the bloc

Elements	Quantity
Sika BV 3M	0,07009
Crushed LECA Position 5 [kg]	22,83
Cement (32,5) [kg]	11,41
Water [L]	11

At the same time, Pierre Latteur and Sébastien Goessens are developing other designs and the compositions are not yet defined. Moreover, it is easy to assume that many other prototypes will be produced in the future with different properties. Therefore, in this study we are only taking into account the geometrical properties elaborated by A. Naveau and A. Moncourrier.

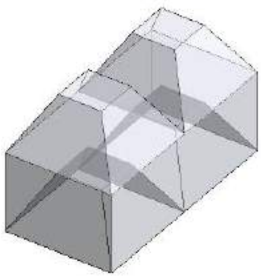

Figure 21 : Masonry block for a drone-built wall.[37]

There are 443,43m^2 of walls in the Manhay house. According to the information above, this will require 7390 bricks. Consequently, the drone will have to be charged 174,5 times. Using an emission factor of 0,22 $KgEqCO_2$/kWh, the construction emission for all the walls is 38,39 kg of CO_2.

3.2.3 Floors

The girder-slab system is an elementary approach when considering a drone-built floor. The system consists of support beams (girders) which will bear weight of the slabs, settled between two beams. This technology is in use by workers, but is slow and therefore has a high labor cost. However, the drone has a low labor cost and can be time efficient. The right-hand side of Figure 22 illustrates the system, while the left-hand side provides its dimensions in millimeters.

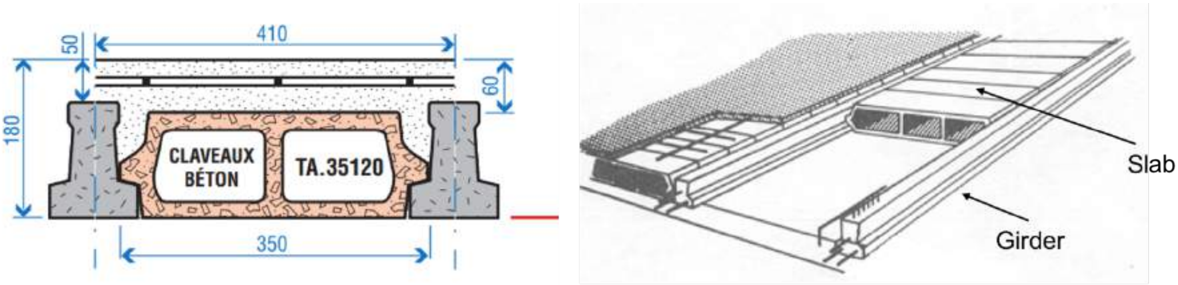

Figure 22 : Girder - Slab system and dimensions. [73] [74]

Maisons Blaviers ordered 161,9m^2 of hourdis to build the ground floor and first floor. This will be replaced by 1651 slabs of a length of 20cm. There are 10,2 small slabs per meter square. It takes 35 seconds for a drone to install a slab and is loaded during 25s. The girders are 8 meters long and 30 of them are required to carry all the slabs. A girder weighs 20kg/m. In addition, it is presumed that there will be one drone per meter. Altogether, we will need 45 charges to build both floors. Using an emission factor of 0,22 KgEqCO_2/kWh, the construction emission for two floors is 9,85 kg of CO_2.

3.2.4 Transport

As above analysis demonstrates, drones will build the walls in 71,85 hours while the floors will be completed in 18,24 hours. Because a drone can work for 24 hours straight (excluding charges), the technicians will be organized into 3 shifts of eight hours. Only one technician is needed at a time, so three cars will be driven to and from the construction site per day. The transport emissions of the drones and technicians for both walls and floors are 103,6kg and 34,55kg of CO_2, respectively.

3.2.5 Life Cycle Impact Assessment

The total climate change impact of the material production, transport, construction, maintenance, operating and demolishing is 413,17 tons equivalent of CO_2, which represents an impact of 2,152 tons eq CO_2 per meter-square of heated floor. The value of CO_2 eq emission and energy consumption for each phase can be found in Table 5. In the construction phase we added 186 KgEqCO_2 but subtracted 428 KgEqCO_2 (for the machines and workers' travels).

Table 5: Energy consumption and CO2 eq emission during the drone built Manhay house life cycle

	Energy [kWh/(m2)	Greenhouse gas emission [KgEqC02/(m2)]
Material production	4678,8	624,6
Construction process	622,33	134,17
In use	7410	1290
End of life	315,6	103,2

Even though the results are consistent with the literature, the outcome is surprising. The first assumption made at the outset of this study claimed that the drone would increase significantly the emissions during the construction phase. However, as it is demonstrated in Figure 23, this is not the case. The use phase has the largest impact with 60 percent, followed by the material production, the construction process and finally the demolition process. Figure 24 illustrates the importance of each element linked to a drone-built architectural structure. We can see that the drone's consumption does not have a significant influence on emissions produced. The impact generated by the technicians' travels is much larger, comparatively. In section 3.3 we will discuss the difference between the human and drone-built house.

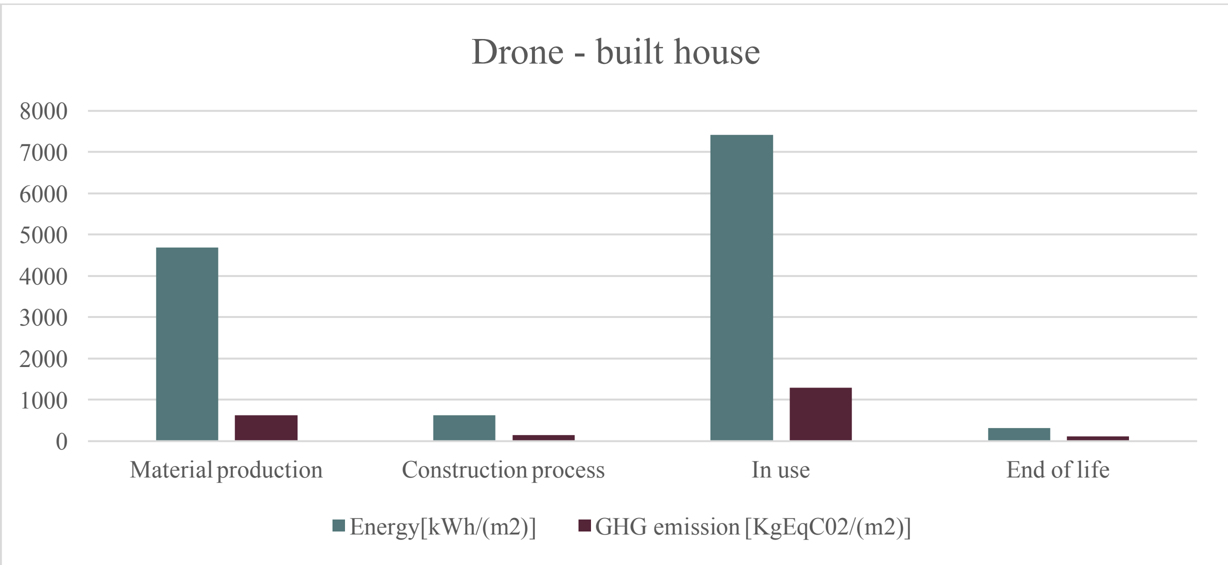

Figure 23 : CO2 emission break down between the different phases of the drone-built house

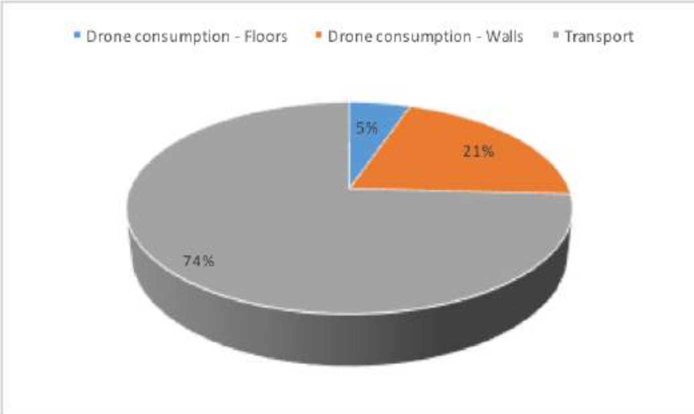

Figure 24 : GHG emissions during the construction with drones.

3.2.6 Potential improvements

We have defined three factors which have an important impact on the results. First, the length and height of the bricks used have proven to sway the results. At the present time, the bricks' dimensions are 40x15 centimeters. If we half the size of the bricks, it will double the energy needed. Accordingly, if we use 30cm high bricks, it will reduce half the consumption.

Secondly, the number of drones used simultaneously also impacts the emissions produced. By increasing the number of drones working simultaneously, we decrease the construction time without changing the overall consumption. An advantage of simultaneous use is the possibility to reduce the overall number of technician shifts and therefore cut emissions related to the transport. In other words, if we add two more drones, we would reduce the GHG emissions due to technicians' travel by 67 percent. However, Figure 25 demonstrates that this decrease in CO_2 is not infinite. If we greatly increase the number of drones working simultaneously beyond 9, the emissions outcome will no longer decrease for each additional drone used. All the values are detailed in Table 6.

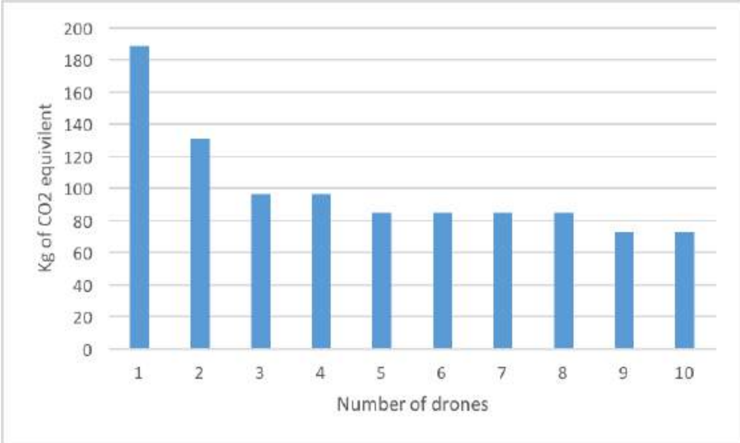

Figure 25 : GHG emission during the construction with drones varying in function of the number of drones working simultaneously.

Table 6 : Variation of the GHG emissions in function of the number of drones working simultaneously.

	N° of drones									
	1	2	3	4	5	6	7	8	9	10
Floors [KgEqCO2]	9,84	9,84	9,84	9,84	9,84	9,84	9,84	9,84	9,84	9,84
Execution time [hours]	18,42	9,21	6,14	4,60	3,68	3,07	2,63	2,30	2,05	1,84
Walls [KgEqCO2]	38,39	38,39	38,39	38,39	38,39	38,39	38,39	38,39	38,39	38,39
Execution time [hours]	71,85	35,93	23,95	17,96	14,37	11,98	10,26	8,98	7,98	7,19
Transport [KgEqCO2]	138,22	80,63	46,07	46,07	34,55	34,55	34,55	34,55	23,04	23,04
Total [KgEqCO2]	**186,45**	**128,86**	**94,30**	**94,30**	**82,78**	**82,78**	**82,78**	**82,78**	**71,27**	**71,27**
Total GHG reduction obtained by adding 1 drone [%]	0	30,89	26,82	0	12,21	0	0	0	13,91	0

Finally, the last important factor is the energy source. In section 3.1.3 we discussed the different energy productions found on Belgium's electricity grid. Instead we could imagine producing our own electricity by installing photovoltaic panels on the van transporting the drones. An ordinary van has more or less $6m^2$ of roofing. According to the Belgium company Energreen [38], with $6m^2$ it is possible to install 15 panels, each producing 250W. With a performance of 80 percent, this would translate to a maximum production of 3kWh. This level of energy production would be enough to supply one drone working constantly. Even though this figure is only a rough estimation we could attempt to combine the panels with Tesla's Powerwall.[6] [39]

3.3 Conclusion

Given the information above, it is now possible to compare the house built by workers and the one with the floors and walls built by a drone. First, we will briefly review the results obtained from each case before analyzing the differences. In order to compare the effect of the drones against the workers, we focus on the parts of the life phases that differ between the two cases, namely the construction phase.

The disparity noticed in Figure 26 is very small, 1,254 $KgEqCO_2/m^2$ of heated floor. That is to say, the drone-built house saves up 240 kg of CO_2 in total for the entire house. This represents a reduction less than one percent of emissions over the workers' construction process and not even 0,1 percent of the overall life-cycle. Considering the findings of Table 6, we can optimize the savings up to 356kg by having 9 drones working simultaneously. This reduction represents only 1,37 percent of the construction emission. Nevertheless, as there are more than 40 000 new housing units built in Belgium per year,[40] the method has a potential of reducing transport emissions by 0,01424 Mt eq CO_2/year in addition to the 25,26 Mt eq CO_2 emitted annually by transport in Belgium.[41]

[6] The Tesla Powerwall is a domestic rechargeable battery, which has the capacity to stock 6,4 kWh per battery.

	Energie [kWh/(m2)]	GHG Emission [KgEqC02/(m2)]
Material production	4678,8	624,6
Workers' construction process	625,6235857	135,4709731
Drones' construction process	620,0427666	134,2166282
In use	7410	1290
End of life	315,6	103,2

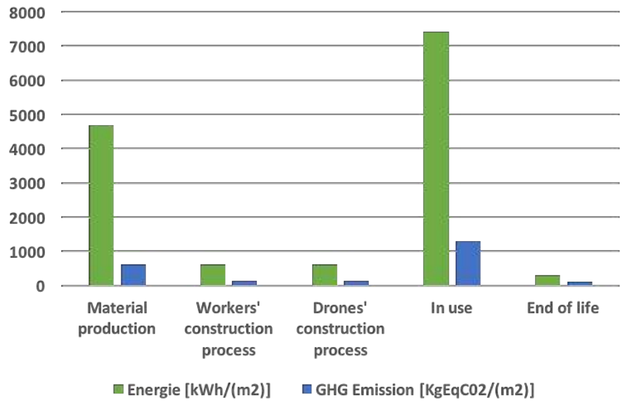

Figure 26 : Environmental impact comparison between the human and drone built house.

The drone-built house has a lower CO_2 emission because of its significant reduction in transport-related emissions. While the human-built house has two vans per day driving up to the site during 15 days for the walls and 2 days for the floors, the drones need only 3 to 12 round trips for both walls and floors. The drone consumption is slightly higher than the machines used by the workers: 262 $gEqCO_2/m^2$ and 197 $gEqCO_2/m^2$, respectively. Moreover, as shown in Figure 24, the impact from the electricity needed is significantly lower than transport.

In conclusion, building with drones enables emissions reduction linked to transport, which is particularly noteworthy as transport is biggest contributor to the construction's climate change impact. Given these findings a drone-built architectural structure has a more positive environmental impact than a human-built house; however, for a more thorough and detailed analysis, a study should incorporate the production of the construction materials.

4 Financial feasibility of a drone-built architectural structure

"Only when your product is 10x better can you offer the costumer transparent superiority[42]", Peter Thiel.

Chapter 3 showed that the carbon footprint of a drone-built architectural structure is slightly more environmentally friendly than entirely man-made building. But, is the product 10 times financially better?

This chapter will first review the overall price of building a standard house. Then we will detail the prices for masonry walls and floors using prefabricated elements. In a third part, the cost of drone-built walls and floors will be studied. The analysis includes the materials necessary to carry out the construction. Finally, a financial comparison will be drawn between the two scenarios. The comparison will be based on a standard house chosen by the CSTC. The choice of the house is explained in section 4.1. To properly answer the financial feasibility question, it is essential to take into account the cost as well as the time. It is important to note that all prices stated below exclude the value added tax (VAT).

4.1 Opticost

Opticost is a project launched end of 2014 by the CSTC. They observed that construction prices were increasing though household earnings were not following that trend. Nevertheless, they estimate that by 2040, Wallonia will need to shelter 350.000 new households. Moreover, obtaining financial help for mortgages is increasingly difficult. [43] Given such information, the study's goal is to establish some tools to lower the prices of new constructions, without forgoing quality. Therefore, Opticost created a working group composed of key companies from the residential sector (i.e., Maisons Blaviers). This enabled them to have direct access to relevant data. They have studied the different construction systems and factors linked to the costs.

Opticost based their studies on two scenarios: one single-family house and one apartment. For their single-family house, the working group selected a standard two level house which is commonly built in Belgium. The house plans are shown in Figure 27. It is 10,59 meters long and 6,99 meters large. The bill of quantities and plans can be found in Annex 3 and 4. As this study is limited to the case of a single-family house, our study will also use the standard house as an example.

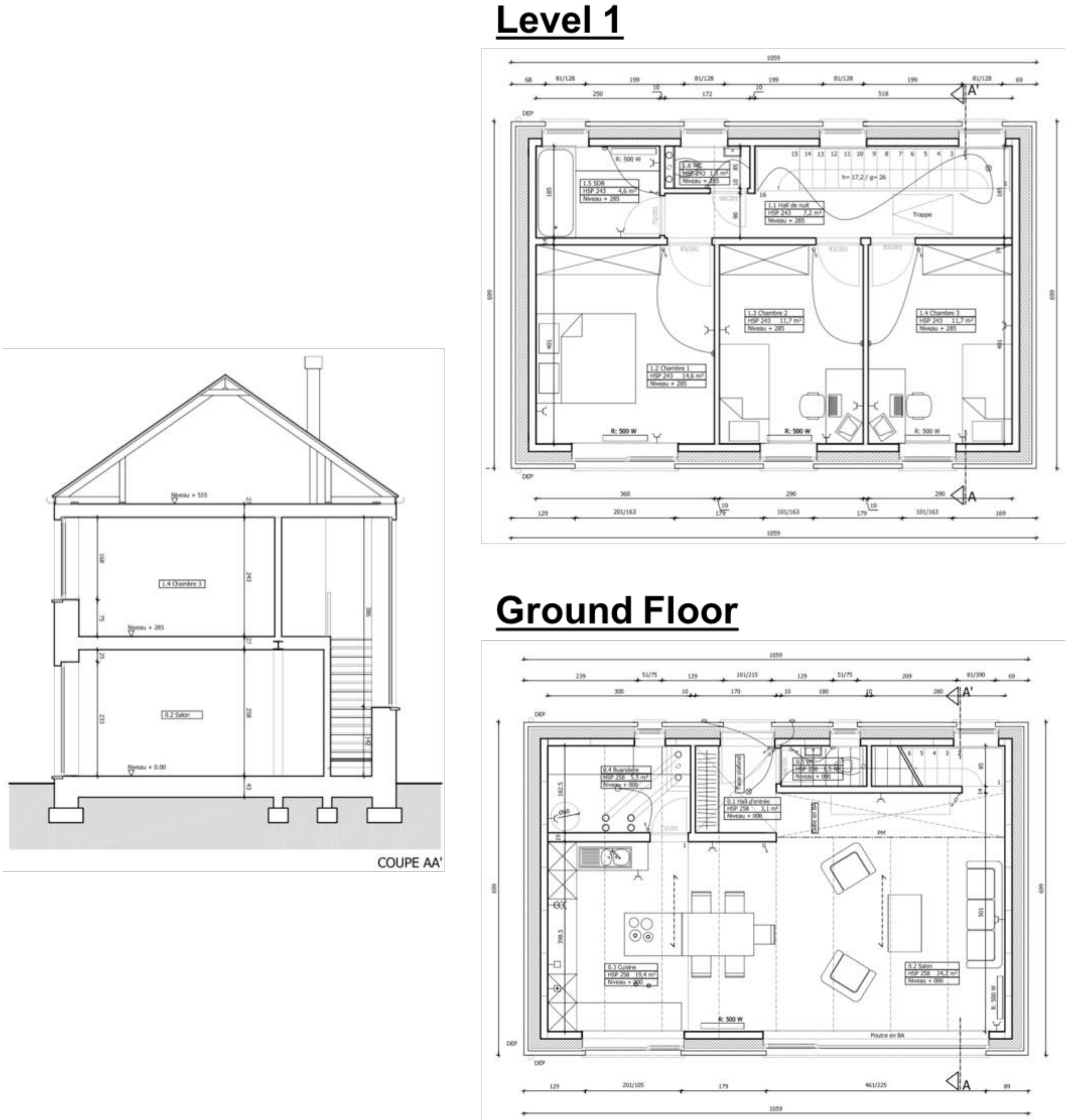

Figure 27 : Opticost's standard house.[43]

4.1.1 Planning

The house is scheduled to be built in eight calendar months, or 133 open days, based on a leap year containing 366 days.[44] From 366, we subtracted: 104 week-end days, 20 annual holidays, 12 compensatory leave, 10 public holidays and 20 days for the weather. This leaves 16,67 working days per month.

Planning			Total time = 133 open days ou 8 calendar months							
	Work description	Open days	1 month	2 month	3 month	4 month	5 month	6 month	7 month	8 month
1	Site installation	10 Open days								
2	Prepatory work	5 Open days								
3	Groundwork and drainage	5 Open days								
4	Floor slab	5 Open days								
5	Stability - Ground floor	20 Open days								
6	Stability - Level 1	15 Open days								
7	Facade	15 Open days								
8	Roof	10 Open days								
9	Exterior woodwork	5 Open days								
10	Cladding walls	10 Open days								
11	Cladding ceiling	10 Open days								
12	Cladding floor	10 Open days								
13	Interior wood finish	5 Open days								
14	Electricity, ventilation, heating and sanitary	110 Open days								
15	Various finishings	8 Open days								
16	Weather and statutory holidays	Included								

Figure 28 : Work planning for the standard single house. [75]

Later we will develop the cost of building walls and floors with and without drones. Important to note in Figure 28 is the time needed for the stability and facade, 35 days (26,32 percent of total time) and 15 days (11,27 percent), respectively. The stability includes the walls (8 to 10 days), the beams (5 to 6 days) and the upper slab (5 days).

4.1.2 Cost

The cost of a construction can be defined by three key factors: labor cost, material cost and equipment need. Table 7 includes a fourth column for subcontracting. Maisons Blaviers and other companies hire externals contractors to reduce their work load and responsibilities. What we can notice from these numbers is the importance of the exterior walls which are equal to nearly 25 percent of the overall price. Another key ratio is the workforce price over the material and equipment, which is greater than 1. Excluding subcontractors, the workforce represents 50,9 percent of the total cost.

Table 7 : Individual housing - Cost by work.[43]

	Description	Material	Workforce	Equipment	Subcontracting (SC)	Total	%
1	Site installation	170,00 €	105,00 €	2.487,48 €	3.410,00 €	6.172,48 €	4,28%
2	Earthworks	0,00 €	0,00 €	0,00 €	3.405,60 €	3.405,60 €	2,36%
3	Drainage	0,00 €	0,00 €	0,00 €	3.223,54 €	3.223,54 €	2,23%
4	Foundations	2.377,10 €	3.869,11 €	0,00 €	0,00 €	6.246,21 €	4,33%
5	Floor - Ground floor	3.915,65 €	1.436,54 €	0,00 €	0,00 €	5.352,19 €	3,71%
6	Exterior walls : Facade	14.622,06 €	18.585,74 €	0,00 €	0,00 €	33.207,80 €	23,00%
7	Exterior woodwork	0,00 €	0,00 €	0,00 €	9.422,36 €	9.422,36 €	6,53%
8	Roof	0,00 €	0,00 €	0,00 €	16.196,45 €	16.196,45 €	11,22%
9	Interior bearing wall	577,92 €	1.260,72 €	0,00 €	0,00 €	1.838,64 €	1,27%
10	Interior floor	2.672,85 €	1.796,94 €	0,00 €	5.709,28 €	10.179,07 €	7,05%
11	Interior partition wall	0,00 €	0,00 €	0,00 €	1.468,20 €	1.468,20 €	1,02%
12	Interior woodwork	0,00 €	0,00 €	0,00 €	8.568,69 €	8.568,69 €	5,93%
13	Interior cladding - floors	0,00 €	0,00 €	0,00 €	7.241,14 €	7.241,14 €	5,02%
14	Interior cladding - walls	0,00 €	0,00 €	0,00 €	4.772,84 €	4.772,84 €	3,31%
15	Heating system	0,00 €	0,00 €	0,00 €	6.724,80 €	6.724,80 €	4,66%
16	Domestic hot water system - Sanitary	0,00 €	0,00 €	0,00 €	11.486,66 €	11.486,66 €	7,96%
17	Ventilation system	0,00 €	0,00 €	0,00 €	3.000,00 €	3.000,00 €	2,08%
18	Electric system	0,00 €	0,00 €	0,00 €	5.876,96 €	5.876,96 €	4,07%
	Total	**24.335,58 €**	**27.054,05 €**	**2.487,48 €**	**90.506,52 €**	**144.383,63 €**	*100,00%*
	Percentage of the nature of the work	**16,855%**	**18,738%**	**1,723%**	**62,685%**	**100,00%**	

Total of direct expenses (DE)	**24.165,58 €**	**26.949,05 €**	**0,00 €**	**87.096,52 €**	**138.211,15 €**	
Discount on materials (3%) and SC (7%)	**-724,97 €**			**-6.096,76 €**	**-6.821,72 €**	
Total of indirect expenses (On site installation) (IE)	**170,00 €**	**105,00 €**	**2.487,48 €**	**3.410,00 €**	**6.172,48 €**	4,47%
Total of direct and indirect expenses	**23.610,61 €**	**27.054,05 €**	**2.487,48 €**	**84.409,76 €**	**137.561,91 €**	

4.2 Human cost

Section 4.1.2 gave a general view of the different costs associated with building the house. In this section, we will delve deeper into the walls and floors, including the façade, exterior walls, bearing interior walls, partition walls and the level 1 floor. First, the labor cost is analyzed, and then, the materials' prices are studied. After all things are considered, the costs comparable with the drone method, are summarized in one table.

The ground floor slab is cast on site as a drone is not yet capable of executing such task. Therefore, we have chosen not to integrate this element into our analysis.

4.2.1 Labor Cost

Labor cost is particular to the construction's geographic location. Depending on which continent or country the work is executed, the labor cost will vary significantly. By simply crossing a border, the cost can double. Many surveys have been done by the European Commission to establish these differences. Table 8 shows that Norway is the European country with the highest paid labor (46,9€/h), and Bulgaria has the lowest hourly rate (3,2€/h).[45]

Table 8 : Labor costs per hour in euro, breakdown by economic activity, 2014.[45]

	Business economy	Industry	Construction	Services	Mainly non-business (excl. public admin.)
EA18	**29.2**	**32.0**	**25.8**	**28.2**	**29.1**
EA19	**29.0**	**31.8**	**25.6**	**28.0**	**28.9**
EU	**24.5**	**25.5**	**22.0**	**24.3**	**24.7**
Belgium	41.1	44.1	34.4	40.6	34.1
Bulgaria	3.8	3.7	3.2	4.0	3.8
Czech Republic	9.6	9.6	8.7	9.8	8.6
Denmark[6]	42.0	42.1	36.5	42.6	37.1
Germany	31.8	37.1	25.5	29.0	30.2
Estonia	10.2	9.8	11.5	10.4	8.6
Ireland	28.4	32.1	26.7	27.2	33.8
Greece	14.4	15.6	12.7	14.2	15.1
Spain[6]	21.0	23.5	20.8	20.2	22.2
France	35.2	37.0	30.4	35.1	32.7
Croatia	9.4	8.5	8.3	10.0	9.6
Italy	27.4	28.0	24.7	27.2	32.3
Cyprus	15.7	14.8	14.4	16.1	17.7
Latvia	6.6	6.2	6.5	6.9	6.5
Lithuania	6.6	6.3	6.5	6.8	6.1
Luxembourg	35.7	32.0	24.8	38.6	37.4
Hungary	7.8	7.7	6.4	8.0	5.9
Malta	11.8	11.8	9.6	12.1	14.0
Netherlands	33.5	c	c	c	c
Austria	31.7	34.9	30.5	30.3	30.6
Poland	8.2	8.4	7.2	8.1	9.0
Portugal	12.6	10.7	11.5	14.0	14.4
Romania	4.8	4.7	3.4	5.1	4.1
Slovenia	15.5	15.8	11.6	16.1	15.7
Slovakia	10.0	10.1	8.2	10.2	8.7
Finland	32.9	35.9	33.7	31.4	31.0
Sweden	40.2	41.8	38.4	39.7	32.8
United Kingdom	22.2	22.6	22.3	22.1	22.5
Norway	54.6	63.8	46.9	51.7	51.1

Belgium is just behind Denmark with an hourly labor cost of €34,4. It is important to note that this rate includes taxes and applies uniquely to declared workers. Though illegal, some companies employ non-declared workers who cost €10 to €13 per hour.[46] It is possible, however, to legally employ foreign workers due to the E.U. free movement of workers policy.[47] Eurokontact is a company based in Wroclaw (Poland) which offers such a service. Their work force costs between €14 and €20 per hour.[48] For the rest of the study we will make the same hypothesis as the CSTC, which is to take an hourly rate cost of €35.

4.2.2 Materials

It is important to understand that a wall is not just a pile of blocs. We have to differentiate between the various layers, especially as today's drones are not able to build all of the layers.

Table 9 is a summary of the costs for the walls and floor, which are detailed further below. The values are consistently in unit price (UP) and include all the layers. That is to say, the cost to build 1 m^2 of a wall or floor. The execution time is based on the average work done by 1 worker.

Table 9 : Unit price and time for the walls and level 1 floor.

		Material	**Workforce**		**Equipment**	**Total unit price**
	Units	UP Material	*Exec. Time*	UP WF	UP Equipment	**Total UP**
Walls						
Facade						
Bricks	m^2	33,70 €	95min	55,43 €	12,00 €	101,13 €
Expanded clay blocs - 14cm	m^2	13,43 €	70min	40,78 €	2,50 €	56,71 €
Interior bearing wall						
Expanded clay blocs - 14cm	m^2	12,31 €	56min	32,69 €	2,50 €	47,50 €
Expanded clay blocs - 19cm	m^2	18,56 €	75min	43,40 €	2,50 €	64,46 €
Interior partition wall						
Expanded clay blocs	m^2	9,35 €	45min	26,15 €	2,50 €	38,00 €
Floors						
hourdis	m^2	43,95 €	31min	17,95 €	0,00 €	61,90 €

Walls

Façade

The façade is built using two kinds of blocs [44]:

- Bricks
    - Dimensions (L x l x h): 212x101x65mm
    - Execution time: 95min/m^2

    - Price: 45,7€/m^2
        - 25,54€/m^2 for the bricks
            - Execution time: 90min/m^2
        - 1,94€/m^2 for the mortar
        - 2,2€/m^2 for the reinforcement
        - 1,47€/m^2 for the metal angles
        - 12€/m^2 for the scaffolding
        - 2,55/m^2 for various materials

- <u>Expanded clay blocs – 14cm thick</u>
    - Dimensions: 390x140x190mm
    - Execution time: 70min/m^2
    - Price: 15,93€/m^2
        - 8,65€/m^2 for the blocs
            - Execution time: 42min/m^2
        - 1,27€/m^2 for the mortar
        - 0,31€/m^2 for the waterproof layer
        - 0,94€/m^2 for the reinforcement
        - 0,76€/m^2 for the lintels
        - 2,5€/m^2 for the scaffolding
        - 1,5/m^2 for various materials

- The insulation is not taken into account as the drones are not yet capable to accomplish such task and therefore it is not comparable.

Interior bearing wall

Two different thicknesses are used for the interior bearing walls [44]:

- <u>Expanded clay blocs – 14cm thick</u>
    - Dimensions (L x l x h): 390x140x190mm
    - Execution time: 56min/m^2
    - Price: 14,81€/m^2
        - 8,65€/m^2 for the blocs
            - Execution time: 42min/m^2
        - 1,27€/m^2 for the mortar
        - 0,18€/m^2 for the waterproof layer
        - 0,71€/m^2 for the lintels
        - 2,5€/m^2 for the scaffolding
        - 1,5/m^2 for various materials

- Expanded clay blocs – 19cm thick
    - Dimensions: 390x190x190mm
    - Execution time: 75min/m^2
    - Price: 21,06€/m^2
        - 14,33€/m^2 for the blocs
            - Execution time: 51min/m^2
        - 1,72€/m^2 for the mortar
        - 0,53€/m^2 for the waterproof layer
        - 0,48€/m^2 for the lintels
        - 2,5€/m^2 for the scaffolding
        - 1,5/m^2 for various materials

Partition wall

The partition walls are made of expanded clay blocs which are 9cm thick. Generally, a company is subcontracted to construct the walls for a total cost of 42€/m^2. This quota includes all expenses. To estimate the proportion of each factor, we assumed the unit price of the workforce and material was 20 percent lower than the 14cm thick walls, which translates to an execution time of 45min/m^2 and 11,85€ for the material.

Floor – level 1

The first level floor is composed of both prefabricated elements (hourdis) and concrete casted on site. As the drones are only able to aid with the prefabricated elements at this point, we only compare the prefabricated elements.

- Hourdis
    - Dimensions: 395x60x13,5cm
    - Execution time: 31min/m^2
    - Price: 43,95€/m^2
        - 28€/m^2 for the hourdis
            - Execution time: 15min/m^2
        - 7,48€/m^2 for compression screed
        - 2,8€/m^2 for the concrete pump
        - 0,4€/m^2 for the concrete pumping supplement
        - 3,77€/m^2 for the reinforcement
        - 1,5/m^2 for various materials

4.2.3 Conclusion

To conclude, the cost to build a wall or floor depends on the layers constituting them. Given the information above, the most expensive layer is the blocs, the bricks or the hourdis. As previously mentioned, presently, a drone can only move around and stack blocs together. It cannot build the framework, pour the concrete or place the reinforcements. Later, when the costs are compared between the human workers and the drone, we will only consider the blocs, the mortar, the lintels and the scaffoldings. All these elements are summarized in Table 10.

It is essential to highlight the importance of the workforce on the wall cost. The labor price can reach 69 percent of the total price (for the walls composed of 14cm thick expanded clay blocs). Meanwhile, the hourdis cost is three times more expensive than the workforce.

Table 10 : Simplified unit price and execution time, which will be compared with the drones.

		Material	**Work force**		**Equipment**	**Total unit price**
	Units	UP Material	*Exec. Time*	UP WF	UP Equipment	**Total UP**
Walls						
Facade						
Bricks	m^2	27,48 €	90min	52,50 €	12,00 €	91,98 €
Expanded clay blocs - 14cm	m^2	10,67 €	52min	30,10 €	2,50 €	43,27 €
Interior bearing wall						
Expanded clay blocs - 14cm	m^2	10,63 €	51min	29,75 €	2,50 €	42,88 €
Expanded clay blocs - 19cm	m^2	16,53 €	60min	29,75 €	2,50 €	48,78 €
Interior partition wall						
Expanded clay blocs	m^2	8,50 €	41min	23,80 €	2,50 €	34,80 €
Floors						
hourdis	m^2	28,00 €	15min	8,75 €	0,00 €	36,75 €

4.3 Drone cost

This sub-chapter analyzes the factors influencing the cost of a drone-built architectural structure. The study is limited to the walls and floors of the house. First, four factors are identified:

the materials, the equipment, the technicians and the fixed costs. Second, the number of drones is optimized to obtain the lowest cost. Finally, the costs are summarized in a small conclusion.

Many hypotheses had to be made as the technology is not yet ready. These hypotheses are noted at the beginning of each section.

4.3.1 Materials

Walls

Hypotheses:

- The materials' dimensions used by drones are the same as the ones used by the workers.[7]
- The prices are assumed to be the equal or 30 percent higher than the existing blocs.

According to Josephe Gillet, who works at Béton de la Lomme,[8] to produce the bloc described in section 3.2.2, would cost €10 per bloc. At that price, the blocs are fabricated using molds which cost €1000 to €1.500 per mold. The high cost can be explained by the complexity of the bloc. It is composed of two separated holes, which make it impossible to manufacture with the traditional machines. If this production were the only option, a drone-built wall would not be financially advantageous, despite the potential positive environmental benefits, and the drone method would be cast aside.

The solution is to build a new production line with a machine specially designed to produce this kind of shape. The cost of this project could easily reach €25 million, and the demand for this type of blocs would need to be high as the production capacity would be massive (3200 blocs per hour).

Evidently, the first option is not feasible. The second option would require the construction of a new factory which extends beyond the scope of this research. We will, therefore, assume that drone compatible blocs will cost the same price as the existing blocs. To incorporate a pessimistic analysis, we will add a second scenario where material prices are 30 percent higher.

[7] As a reminder, the dimensions are detailed in section 4.2.2.

[8] Béton de la Lomme is a Belgian company, based in Rochefort, which is specialised in concrete fabricated elements. Their annual turnover is fourteen million euros.

Floors

Hypotheses:

- The drones use the girder – slab system[9] to build the level 1 floor.
- The prices are assumed to be the same as the existing girders and slabs.

The main advantage of the girder – slab system is its small elements which make it drone-compatible. The slabs have a dimension of 49x20x12cm (b x L x E shown in Figure 29)) and weigh 12,1kg per unit. The girders are 3,6m long. Bigmat[10] provided a quote for these elements: €1,11 for the slabs and €39,18 for the girders.

Figure 29 : Illustration of a slab used for the girder - slab system. [76]

Conclusion

Table 11 summarizes the prices per m² for each type of walls. In scenario 1, the materials are the same price as the existing materials. In scenario 2, the materials are 30 percent more expensive.

[9] The girder-slab system is described in section 3.2.3.

[10] BigMat is a network of 25 Belgian distributors specialized in building materials.

Table 11 : Drone compatible material cost.

		Material Scenario 1	**Material Scenario 2**
	Units	UP Material	UP Material
Walls			
Facade			
Bricks	m^2	27,48 €	35,72 €
Expanded clay blocs - 14cm	m^2	10,67 €	13,87 €
Interior bearing wall			
Expanded clay blocs - 14cm	m^2	10,63 €	13,82 €
Expanded clay blocs - 19cm	m^2	16,53 €	21,49 €
Interior partition wall			
Expanded clay blocs	m^2	8,50 €	14,37 €
Floors			
Girder - slab	m^2	30,43 €	39,56 €

4.3.2 Equipment

Hypotheses:

- A drone costs €15.000 to purchase.
- The lifetime of a drone is 2.000 hours.
- The electricity cost is 0,13€/kWh.

The equipment includes the drones and the electricity to power them. At the moment, the drone used costs €15.000. It is presumed that the lifetime of a drone is 2.000 hours. The drone's properties are detailed in section 3.2.1 (page 39) These costs lead to an hourly cost of 7,816€/h for each drone (7,5€/h for the drone and 0,316€/h for the electricity). Assuming it takes 35s for a drone to add one element, it can build 7,62m^2 of blocs, 1,417m^2 of bricks or 10,2m^2 of slab in one hour. With this, we can obtain a unit price (€/m^2) for each type of architectural structure. The prices are summarized in Table 12.

Table 12 : Drone's equipment prices per m².

		Equipment
	Units	UP Equipment
Walls		
Facade		
Bricks	m^2	5,514 €
Expanded clay blocs - 14cm	m^2	1,025 €
Interior bearing wall		
Expanded clay blocs - 14cm	m^2	1,025 €
Expanded clay blocs - 19cm	m^2	1,025 €
Interior partition wall		
Expanded clay blocs	m^2	1,025 €
Floors		
Girder - slab	m^2	0,767 €

4.3.3 Workforce

Hypotheses:

- One technician can supervise 10 drones.
- The hourly cost of a technician is 35€/h.

The drones do all the work by themselves. However, it is utopian to believe that nothing will go wrong and that human supervision is unnecessary. We assume that one technician can supervise ten drones; eleven drones will require 2 technicians. The cost of drones will highly depend on the number of drones used as it will determine the number of technicians needed and the time worked (four drones will build a wall four times faster than a solitary drone). The technician cost can be represented by Equation 4-3. The function ceil() rounds up to the nearest integer.

Equation 4-1 :

$$Technician\ cost\ per\ m^2 = \frac{time\ worked \times 35€ \times n° \ of\ tech.}{m^2\ built}$$

Equation 4-2

$$Time\ worked = \frac{m^2\ build}{l \times h} \times 35s \times \frac{1}{n°\ of\ drones}$$

Equation 4-3

$$Technician\ cost\ per\ m^2 = \frac{\frac{1}{l \times h} \times 35s \times ceil\left(\frac{n°\ of\ drones}{10}\right)}{n°\ of\ drones}$$

Table 13 is an array of values for the Equation 4-3. We can observe that the lowest value is reached with every 10th drone. On the eleventh drone we have to pay two technicians and the per unit value increases. These values are accurate for a bloc with dimensions 39x19cm. In section 4.3.5 we demonstrate that the optimal number of drones working simultaneously is 10 for the walls and 1 for the floor. Using these numbers, Table 14 summarize the workforce cost per m^2 for each architectural structure.

Table 13 : Technician cost in function of the number of drones working simultaneously.

	Number of drones												
	1	2	3	4	5	6	7	8	9	10	11	15	20
Technician Cost [€/m^2]	4,59 €	2,30 €	1,53 €	1,15 €	0,92 €	0,77 €	0,66 €	0,57 €	0,51 €	0,46 €	0,83 €	0,61 €	0,46 €

Table 14 : Technician cost per m².

		Workforce	
–	Units	*Exec. Time*	UP WF
Walls			
Facade			
Bricks	m^2	4,24min	2,47 €
Expanded clay blocs - 14cm	m^2	47,23s	0,46 €
Interior bearing wall			
Expanded clay blocs - 14cm	m^2	47,23s	0,46 €
Expanded clay blocs - 19cm	m^2	47,23s	0,46 €
Interior partition wall			
Expanded clay blocs	m^2	47,23s	0,46 €
Floors			
Girder - slab	m^2	5,89min	3,43 €

4.3.4 Management fee

At the moment the costs are the only variable, we will have to pay only if there is something being built. Moreover, at the moment, increasing the number of drones is beneficial. However, there must be a cost related to the increase of our drone stock so we added a fourth cost for the management of the drones and this cost would increase linearly. This cost encompasses the storage, transport or logistics associated with the drone stock. Assuming storage is more or less 4€/m^2 per month and transport is 0,33€/km, we roughly estimated the management fee per drone to €4 a day.[49][50]

4.3.5 Optimization

Hypotheses:

- One technician can supervise ten drones.
- The hourly cost of a technician is 35€/h.
- The management fees are 4€ per drone per day.
- Minimum size of the masonry work: 100m^2.

- Minimum floor size: $50m^2$.

How many drones have to work simultaneously to obtain the minimum construction cost?

To answer the question, we first have to transform the costs into equations, add them together and find the minimum value. The variable "x" is the number of drones. The minimum will depend on four factors: the technician's hourly cost, number of drone one technician can supervise, the management fee and the surface built. We assumed that the minimum size was $100m^2$ for the walls and $50m^2$ for the floors.

Equation 4-4

$$Total\ cost\ (x) = 3x + number\ of\ blocs \times 35s \times \left(7{,}82€ + \frac{35€ \times ceil\left(\frac{x}{10}\right)}{x}\right)$$

The Figure 30 is a graphical representation of the results of Equation 4-4 for a $100m^2$ wall made of 1350 expanded clay blocs. Two minimums are found, at 10 and 20 drones. Twenty drones will do the job twice as fast, but 10 drones is the least expensive case. Therefore, the wall costs will be based on 10 drones working simultaneously. However, this is not the case for a drone-built floor. Figure 31 represents the building cost of a $52m^2$ floor. There is no minimum. The best case scenario is to use one drone. Nevertheless, the analysis should be recalculated for each new area. For example, five drones is the optimal solution to build $1000m^2$ of floor.

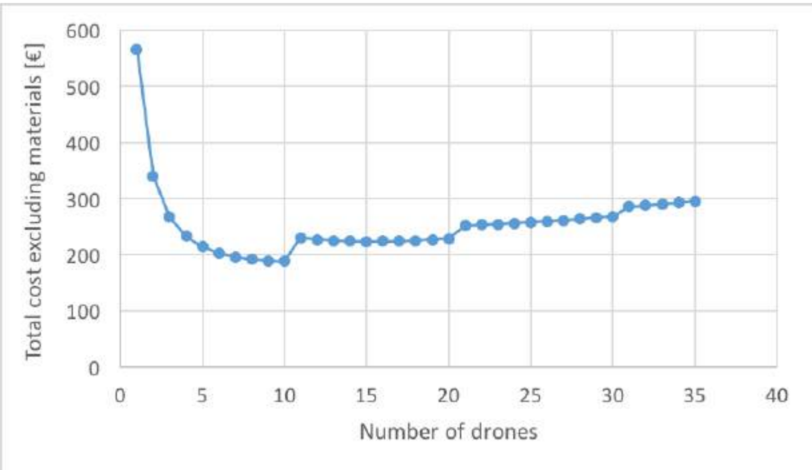

Figure 30 : Total cost to build $100m^2$ wall in function of the n° of drones.

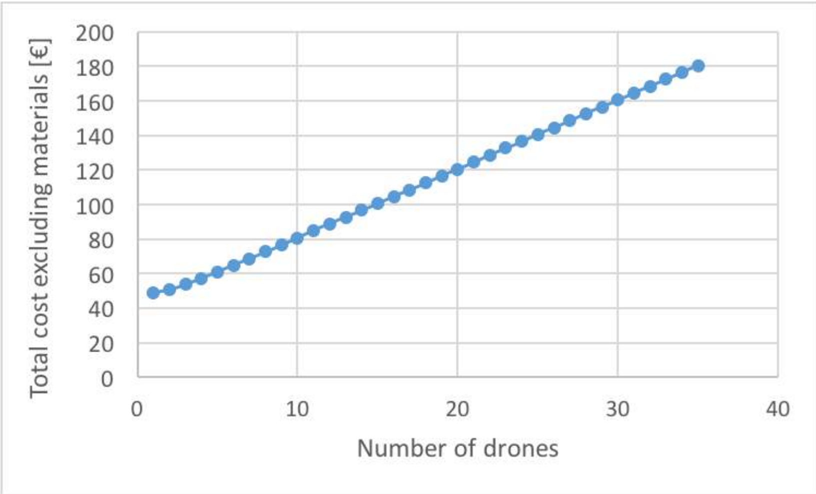

Figure 31 : Total cost to build 52m² floor in function of the n° of drones.

4.3.6 Conclusion

We showed that the cost for building with drones depends on many parameters. The assumptions taken attempt to follow reality at best. We first saw that the production of drone compatible blocs are an issue. The different scenarios were heading outside the scope of the study and therefore we assumed two cases. The first case supposes that the blocs are the same price as existing blocs. While the second case increases the prices by 30 percent. Secondly, we demonstrated that electricity has a small impact on the hourly drone cost, 0,32€/h over 7,82€/h in total. The drone is highly efficient and can reach a performance of 7,62m^2/h. Third, we found that a technician can supervise alone 10 drones. Forth, we calculated a fixed cost of approximately €4 a day per drone. Finally, we demonstrated that the optimized number of drones working simultaneously is 10 for a wall and 1 for a small floor. The costs are summarized in Table 15.

Table 15 : Summary of all the costs related to a drone-built architectural structure.

-		**Material 0% increase**	**Material 30% increase**	**Workforce**		**Equipment**	**Total unit price case 1**	**Total unit price case 2**	**Management fees**
	Units	UP Material	UP Material	*Exec. Time*	UP WF	UP Equipment	**Total UP**	**Total UP**	MF/day
Walls									
Facade									
Bricks	m²	27,48 €	35,72 €	4,24min	2,47 €	5,52 €	35,47 €	43,71 €	40,00 €
Expanded clay blocs - 14cm	m²	10,67 €	13,87 €	47,23s	0,46 €	1,03 €	12,16 €	15,36 €	40,00 €
Interior bearing wall									
Expanded clay blocs - 14cm	m²	10,63 €	13,82 €	47,23s	0,46 €	1,03 €	12,12 €	15,31 €	40,00 €
Expanded clay blocs - 19cm	m²	16,53 €	21,49 €	47,23s	0,46 €	1,03 €	18,02 €	22,98 €	40,00 €
Interior partition wall									
Expanded clay blocs	m²	8,50 €	14,37 €	47,23s	0,46 €	1,03 €	9,99 €	15,86 €	40,00 €
Floors									
Girder - slab	m²	30,43 €	39,56 €	5,89min	3,43 €	0,77 €	38,63 €	47,76 €	4,00 €

4.4 Comparison

It is now possible to compare the cost between a drone and a human worker. The comparison is broken down in three parts. For each factor the costs are summarized in a table, then the differences are outlined and commented upon.

4.4.1 Materials

In both scenarios, the material is clearly the highest cost for the drones. It is responsible for more than 80 percent of the total unit price. Another key point is that the materials used by the girder-slab system are more expensive than hourdis. This will have a decisive impact on the total cost of the floor and led to a higher cost than the hourdis overall. Table 16 summarize the cost of material.

Table 16 : Cost of material. Summary for humans and drones.

		Humans	Drones		Humans	Drones	
		Material	**Material Scenario 1**	**Material Scenario 2**	**Total unit price**	**Total unit price scenario 1**	**Total unit price scenario 2**
	Units	UP Material	UP Material	UP Material	**Total UP**	**Total UP**	**Total UP**
Walls							
Facade							
Bricks	m^2	27,48 €	27,48 €	35,72 €	91,98 €	35,47 €	43,71 €
Expanded clay blocs - 14cm	m^2	10,67 €	10,67 €	13,87 €	43,27 €	12,16 €	15,36 €
Interior bearing wall							
Expanded clay blocs - 14cm	m^2	10,63 €	10,63 €	13,82 €	42,88 €	12,12 €	15,31 €
Expanded clay blocs - 19cm	m^2	16,53 €	16,53 €	21,49 €	48,78 €	18,02 €	22,98 €
Interior partition wall							
Expanded clay blocs	m^2	8,50 €	8,50 €	14,37 €	34,80 €	9,99 €	15,86 €
Floors							
Girder - slab	m^2	28,00 €	30,43 €	39,56 €	36,75 €	38,63 €	47,76 €

4.4.2 Equipment

The principal equipment for the humans are scaffoldings and this cost can be removed for the drones. However, drones being a tool, we decided to integrate them in this category. For the tool to work it needs electricity; consequently, it was included in the equipment cost. Both scaffoldings and drones are the cause of 6 to 13 percent of the total price. Surprisingly, the drones are twice as cheap as the scaffoldings.

Table 17 : Equipment cost. Summary for humans and drones.

		Humans	Drones	Humans	Drones	
		Equipment	**Equipment**	**Total unit price**	**Total unit price scenario 1**	**Total unit price scenario 2**
	Units	UP Equipment	UP Equipment	**Total UP**	**Total UP**	**Total UP**
Walls						
Facade						
Bricks	m^2	12,00 €	5,52 €	91,98 €	35,47 €	43,71 €
Expanded clay blocs - 14cm	m^2	2,50 €	1,03 €	43,27 €	12,16 €	15,36 €
Interior bearing wall						
Expanded clay blocs - 14cm	m^2	2,50 €	1,03 €	42,88 €	12,12 €	15,31 €
Expanded clay blocs - 19cm	m^2	2,50 €	1,03 €	48,78 €	18,02 €	22,98 €
Interior partition wall						
Expanded clay blocs	m^2	2,50 €	1,03 €	34,80 €	9,99 €	15,86 €
Floors						
Girder - slab	m^2	0,00 €	0,77 €	36,75 €	38,63 €	47,76 €

4.4.3 Workforce

This category compares the workforce cost and execution time between humans and drones. It is extremely performant to have 10 drones working simultaneously on one wall. In the time it takes one human builds 1 m^2 of partition wall, 10 drones can build 52m^2. This time save can be valuable. For example, a client building a new house to rent will get a return on investment sooner. In addition, the price is lower as the workforce will be paid for a shorter period of time. For the man-built home, the workforce cost is responsible for more than half the total. Meanwhile with drones, the technician constitutes more or less 5 percent of the total workforce cost.

Table 18 : Cost of workforce. Summary for humans and drones.

		Humans		Drones		Humans	Drones	
		Work force		**Work force**		**Total unit price**	**Total unit price scenario 1**	**Total unit price scenario 2**
	Units	*Exec. Time*	UP WF	*Exec. Time*	UP WF	**Total UP**	**Total UP**	**Total UP**
Walls								
Facade								
Bricks	m^2	90min	52,50 €	4,24min	2,47 €	91,98 €	35,47 €	43,71 €
Expanded clay blocs - 14cm	m^2	52min	30,10 €	47,23s	0,46 €	43,27 €	12,16 €	15,36 €
Interior bearing wall								
Expanded clay blocs - 14cm	m^2	51min	29,75 €	47,23s	0,46 €	42,88 €	12,12 €	15,31 €
Expanded clay blocs - 19cm	m^2	60min	29,75 €	47,23s	0,46 €	48,78 €	18,02 €	22,98 €
Interior partition wall								
Expanded clay blocs	m^2	41min	23,80 €	47,23s	0,46 €	34,80 €	9,99 €	15,86 €
Floors								
Girder - slab	m^2	15min	8,75 €	5,89min	3,43 €	36,75 €	38,63 €	47,76 €

4.4.4 Conclusion

A table with all the costs aligned can be found in Annex 5. Given the information above and using the bill of quantities, we can conclude that it is financially advantageous to build walls with drones but not floors. The drone-built floor is slightly more expensive due to expensive materials and not any faster. The ideal building for drone use would be a large construction with many walls on each level. This would avoid having to come on site for a short period, wait for the upper slab to be built and come once again.

The standard house, modeled by the Opticost team, is built in 133 open days and costs €137.561,91. While a house using drones for the walls is completed in 113 open days and costs between €120.052,86 and €122.444,22, depending the price of the materials. Consequently, drone-built walls offer transparent superiority. It is 20 times faster and nearly 3 times cheaper.

5 Enterprise Value

Valuing an activity is very hard to do and can be done in a variety of ways which all lead to different figures. The importance is that they tend towards the same conclusion. The objective of this chapter is to prove that a company focusing its activity on building walls with drones will be contributing to its financial success. The purpose is not to obtain a precise figure. Before heading into the analysis, a few key financial principals will be summarized.[51]

- The first essential principal is that present wealth is preferred to future wealth. In other words, €100 today is not worth €100 tomorrow.
- Safe asset is preferred to risky asset.
- More good is preferred to less.

The method used is a discounted cash flow analysis (DCF). This valuation method is applicable to all business in general and often used as a sanity check.[52] The process consists of estimating future earnings. This is to say, the company is worth the present value of its future free cash flows. From the future earnings, debts and other forms of money that not owned by the company are subtracted. A DCF is highly sensitive to the discount rate used and assumptions made to evaluate the future free cash flows (FCF).

The valued company is supposed to be ready for execution, meaning the money invested into the research and development is not taken into account.

5.1 Future free cash flows

In chapter 4 we saw the costs of a wall when built by drones. Now we need to know how many walls there are to build in Belgium and how many constructions will we manage to get. This is defined by the market.

5.1.1 Market

Hypotheses:

- The company is specialized in residential buildings.
- Half of the new residential buildings are made of masonry walls.
- The company's share is 0,25 percent of the market.
- The company has an annual growth of 50 percent the first 10 years.

The first assumption made relates to the kind of building the company will build. We assume residential building expertise as we have the data for a residential house and it is all the most common type in the market studied. Moreover, the size of the Opticost house is the most common found on the market. Therefore, we speculate that on average, the prices of each house are similar to the costs detailed in section 4.1.2.[53]

Even though Figure 32 shows a downtrend, Wallonia expects 435 000 new habitants by 2025. Carlo Di Antonio[11], wishes to build 12 000 new housing per year.[54] Belgium has on average 23.708 new residential buildings per year.[40] We assumed that half of those buildings can be drone-built, which results with a market size of 11.854 new house per year, each worth 137.561,91€.

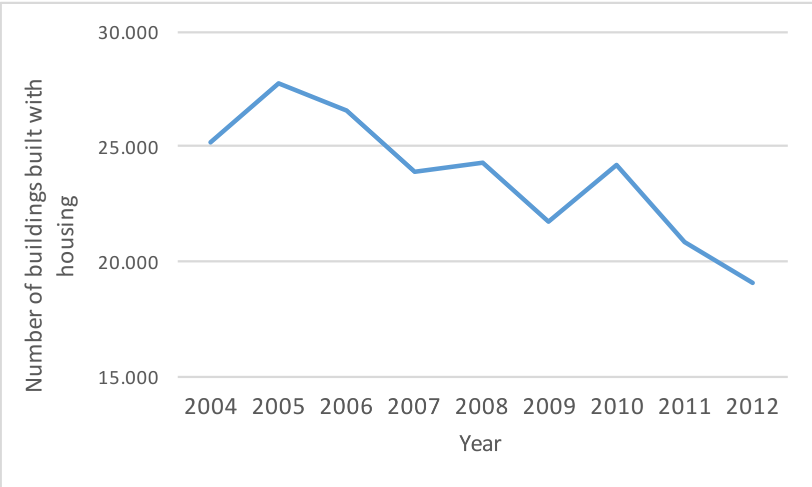

Figure 32 : Number of buildings with housing built per year.[40]

During the first year, the company will manage to secure 30 contracts (0,25 percent of the market). Thereupon, each year, the business will increase their market share by 50 percent. Ending with 9,61 percent of the Belgian market after ten years, or 1140 houses built in one year.

5.1.2 Operating income

Hypotheses:

- Each contract is worth €20.000.
- Cost of goods sold: €10.000 per house.
- SG&A: €2318.
- Marketing budget: 5% of the profit.

[11] Carlo Di Antonio is Wallonia's minister of environment, spatial planning, mobility and transport, airports and animal welfare.

The operating income, or earning before interests and taxes (EBIT), can be calculated by subtracting the operating expenses from the profit. Given the information below, the operating margin is 25,4 percent. Normally a realistic operating margin for residential contractors is 5 to 8 percent.[55] This difference can be explained by the business' low cost of sales (56 percent).

Profit

The company is specialized in building walls. A market is generally not eager to take a large risk and test new technologies with their business future possibly in the balance. Axel Funhoff[12] suggests to show disruptive prices in order to gain more clients. Therefore, the average selling price is settled at €20.000. This is lower than the cost of the human-built walls, which was €27.000 (this price is not even the selling price). This will insure the lowest building price on the market.

Operating expenses

Operating expenses include variable and fixed costs, like labor cost, goods sold, depreciation and office supplies. The good sold is a direct expense and therefore so are the materials and the technician, which total €10.574,62 per house. Sales, general and administrative expenses (SG&A) sum up to €2318 per contract. This includes 7,2 percent of the profit for indirect expenses and 5 percent for the marketing.[56] The depreciation is related to the assets, particularly the drones, owned by the company. Depreciation is function of the profit and represents 6 percent of the costs. The more walls are built, the more drones the business needs.

5.1.3 EBIT to FCF

Hypotheses:

- Days sales outstanding: 30 days.
- Days payable outstanding: 20 days.
- The capital expenditure is equal to 6 percent of the annual revenue.

Increase in working capital

Working capital provides insight into the company's short term financial health. It is the capacity to pay back short term liabilities or debts using current assets. Maisons Balviers pays its contractors within 30 days while Béton de la Lomme asks its clients to pay within 2 to 4 weeks. These values will be subject to negotiations once a term sheet is done.

[12] Axel Funhoff is co-founder and managing partner at Emerald Financing Advisers.

Capital expenditure

Capital expenditure (CAPEX) is the capital used by the business to acquire or upgrade assets. The main assets of the studied company are the drones. Each year the activity grows and consequently so does the number of drones. The investment is estimated to 7 percent of the revenue.

Cash taxes

The corporate income tax in Belgium is generally 33 percent.[57]

5.2 Discount rate

Hypotheses:

- Capital to begin: €1.000.000.
- Debt ratio: 20 percent.
- Risk-free rate: 0,1 percent.[58]
- Equity market premium: 4,5 percent.
- Terminal growth rate: 2 percent.

Like mentioned earlier, future earnings have to be discounted at a certain rate to obtain the net present value. The rate can be defined by the weighted average cost of capital (WACC). The first element to determine is the capital owned by the company. It is assumed that an initial investment of €1 million is needed to set up the activity. The business is new in its domain and highly risky, therefore, only 20 percent of the capital will be funded by bank debt. The final WACC is 9,8 percent.

5.3 Conclusion

To calculate the valuation, we supposed that the technology described in the previous chapters is ready to be used. With the hypotheses mentioned in this chapter, the company has a net present value of €25,8 million. However, this value can change significantly if we alter the market size and share. Our scenario for Belgium is the highlighted blue cell in Table 19. But what happens if we add France, Norway, Germany and other big countries in our market? What happens if we lower our selling price while our number of sales increase? All these parameters make calculating an accurate valuation complicated. Our goal was not to obtain a precise value but to demonstrate that even in a worst case scenario, the company shows a positive net present value. Therefore, we can conclude that a business using drone to build residential walls is a financial success.

Table 19 : What drives the company's value. Possible valuation in millions of euros.

Company's market share after 10 years [%]	Size of potential market - Number of houses: 6000	12000	18000	24000	30000	36000
5	6,6	13,5	20,3	27,2	34	40,9
7,5	10	20,3	30,6	40,9	51,2	61,4
10	13,5	27,2	40,9	54,6	68,3	82
12,5	16,9	34	51,2	68,3	85,4	102,6
15	20,3	40,9	61,4	82	102,6	123,1
17,5	23,7	47,7	71,7	95,7	119,7	143,7
20	27,2	54,6	82	109,4	136,8	164,3

6 Suggested improvement

This work studied the environmental impact and the financial feasibility of a drone-built architectural structure. The scope was limited to a single-family house and more precisely to masonry elements and floors made of prefabricated elements. It is now time to see outside of the scope. Considering the elements analyzed, what are the possible future paths? First a utopian model will be described. Then the author will give his suggestions for future research.

The material production proved to have a significant impact on the energy consumption and climate change. Moreover, some materials are supposed to be used only once and then dumped during the demolition. What if the drone enabled to build walls which can be deconstructed without being torn in pieces? Move from a cradle to gate model to a cradle to cradle scenario. Once a house is decommissioned, the blocks and bricks used would be sent over to a new construction site. In addition to reducing considerably the environmental impact, it would be financially interesting. Two financial models are possible. The elements could be sold to another construction or could have been rented for a long period of time.

In chapter 5 the objective was to study the potential profitability of a company building walls with drones. Such a business had an operating margin of 25,4 percent. There is a more economical way of exploiting such a breakthrough technology. The correct question to ask is: where lies the highest value? Given the costs detailed earlier, the most value is found in the software. The model where the technology discovered is used to start a construction company is not the smartest move. It is like building a great car and using it only to launch a taxi company. It would be, for example, as if Tesla were a taxi company and not a retailer. The added value is not in the wall built but in the software that enabled the drone to build it. Therefore, the smart move is to start a company selling or renting out these special drones. A rough estimation of the gross margin of such a business model could reach 85 percent. This is an incredible financial success. It is not a construction business anymore but an IT startup.

The success of the breakthrough will depend on the materials, the drones and the software managing the drones. If the objective is to bring something quickly on market, the author would focus future research on the software, continue Milan Reniers' work on the dronicks platform,[59] and enable users to easily build their projects and turn them into drone-compatible elements. Meanwhile, a partnership could be founded for the R&D on the drones and materials.

We have seen that the materials make up for the most important costs, therefore this element has to be studied closely. Who is better suited than a professional to find the correct solution? Adrien Naveau and Amoury Moncourier have been working for one year on the perfect bloc. Only mid May were they informed that mass production would be an issue; it took them more or less one day to produce 4 blocs. This could have been avoided by partnering up with a company. We would benefit from their knowledge and resources. The same goes for drones.

7 Conclusion

This work contributes to a bigger project: the will to revolutionize the construction industry with drones. A revolution goes through three steps. At first the innovation is considered silly (this is where the research presently stands). The objective is to demonstrate the feasibility and get the revolution to its next step. This work's goal was to study the environmental and financial potential to build with drones. Many LCAs can be found in the literature but few of them detail the construction process. Furthermore, none of them are compared to drone-built architectural structures. Many websites summarize rough estimations of costs for building a house but none are specific to Belgium. Currently, the CSTC established a research team (OptiCost) to obtain detailed knowledge on Belgian construction costs. This thesis enriches such study with drones' theoretical costs. The research done should enable the reader to answer two questions. Drones are powered by electricity; will the energy needed to lift structural elements be worse than workers for the environment? Is this technology financially interesting?

Chapter 3 puts forward the finding that the energy consumed by the drones has a relatively small impact over the construction of a house and facilitates transport savings. This made it possible to confirm that drones have a lower climate change impact than workers. This diagnosis was found by the analysis of a cradle-to-gate LCA. The latter was based on a 192m^2 house being built by Maisons Blaviers. The analysis of two scenarios was done with the help of the BeGlobal software. In the first scenario, the traditional method using human workers, had a total emission of 413,42 TeqCO_2. In the second scenario, the walls and floors where replaced by drone-built elements, had a global emission of 413,18 TeqCO_2, which ends up by a small saving of 242 kgeqCO_2. This difference is nearly insignificant; it is equivalent to the emission released by a VW Golf Bluemotion driving 9 times from Brussels to Paris.

Chapter 4 established theoretical costs for drone-built walls and floors. The research discovered that the production of drone materials where an issue. Otherwise the overall cost of a wall was cheaper than the human-built elements. Furthermore, the execution time was much faster. It was proved that drone-built floors, however, are not a financial success. The financial study was based on a standard 148m^2 house, which is commonly built in Belgium. First the different layers of each element were identified and detailed, and then we continued the study with the drone-compatible layers. The CSTC certified that the house can be built in 133 open days and would cost €137.561,91. While the research showed that the house with the drone built walls is done in 113 open days and costs 120.052,86€ to 122.444,22€ depending which price we used for the materials. Drone-built walls can be built 20 times faster and at one-third the cost. Thus, drone-built walls are cheap. With the given information a DCF model valued a company specialized in drone built-wall. Even in the worst case scenario, the business was a financial success.

The scope was limited to residential buildings and more precisely single-family houses made of masonry elements. The research focused on the construction process and not the materials used. For a more thorough work, the composition of drone-compatible elements should be taken into account. Moreover, the stability of the drone-built walls has to be studied. The introduction of a method using cement or glue might change significantly the results. Furthermore, the administration costs used in the financial model were based on a traditional construction company. In reality, the drones might require additional supervision.

Throughout this work the financial potential was brought forward. Nevertheless, the technology has great potential in many sectors. According to the author, further research should consider building with wood. In addition to having a better environmental impact than concrete, it is also cheaper. From a financial point of view, the final objective should not be to launch a construction company but an IT startup selling smart drones.

This research enables the construction revolution to continue with the knowledge that drones are financially attractive and do not increase the impact of construction on climate change. In the words of Aberkane, the next step in the drone revolution is for people to consider this technology as dangerous.

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9 Annex

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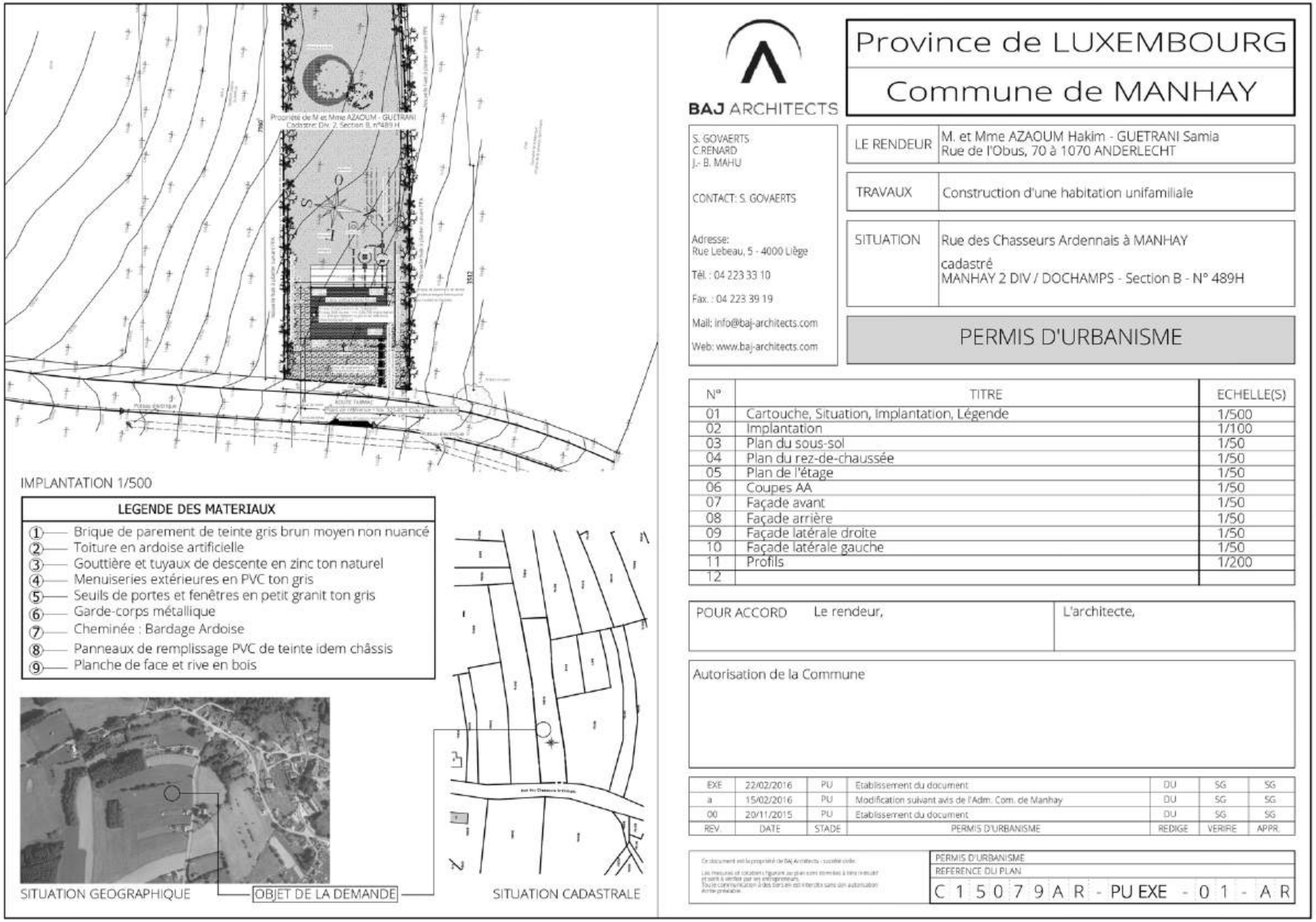
IMPLANTATION 1/500
LEGENDE DES MATERIAUX
① Brique de parement de teinte gris brun moyen non nuancé
② Toiture en ardoise artificielle
③ Gouttière et tuyaux de descente en zinc ton naturel
④ Menuiseries extérieures en PVC ton gris
⑤ Seuils de portes et fenêtres en petit granit ton gris
⑥ Garde-corps métallique
⑦ Cheminée : Bardage Ardoise
⑧ Panneaux de remplissage PVC de teinte idem châssis
⑨ Planche de face et rive en bois
SITUATION GEOGRAPHIQUE
OBJET DE LA DEMANDE
SITUATION CADASTRALE
BAJ ARCHITECTS
Province de LUXEMBOURG
Commune de MANHAY
S. GOVAERTS
C.RENARD
J.- B. MAHU
CONTACT: S. GOVAERTS
Adresse:
Rue Lebeau, 5 - 4000 Liège
Tél. : 04 223 33 10
Fax. : 04 223 39 19
Mail: info@baj-architects.com
Web: www.baj-architects.com
LE RENDEUR
M. et Mme AZAOUM Hakim - GUETRANI Samia
Rue de l'Obus, 70 à 1070 ANDERLECHT
TRAVAUX
Construction d'une habitation unifamiliale
SITUATION
Rue des Chasseurs Ardennais à MANHAY
cadastré
MANHAY 2 DIV / DOCHAMPS - Section B - N° 489H
PERMIS D'URBANISME
N° | TITRE | ECHELLE(S)
01 | Cartouche, Situation, Implantation, Légende | 1/500
02 | Implantation | 1/100
03 | Plan du sous-sol | 1/50
04 | Plan du rez-de-chaussée | 1/50
05 | Plan de l'étage | 1/50
06 | Coupes AA | 1/50
07 | Façade avant | 1/50
08 | Façade arrière | 1/50
09 | Façade latérale droite | 1/50
10 | Façade latérale gauche | 1/50
11 | Profils | 1/200
12
POUR ACCORD
Le rendeur,
L'architecte,
Autorisation de la Commune
EXE | 22/02/2016 | PU | Etablissement du document | DU | SG | SG
a | 15/02/2016 | PU | Modification suivant avis de l'Adm. Com. de Manhay | DU | SG | SG
00 | 20/11/2015 | PU | Etablissement du document | DU | SG | SG
REV. | DATE | STADE | PERMIS D'URBANISME | REDIGE | VERIFIE | APPR.
PERMIS D'URBANISME
REFERENCE DU PLAN
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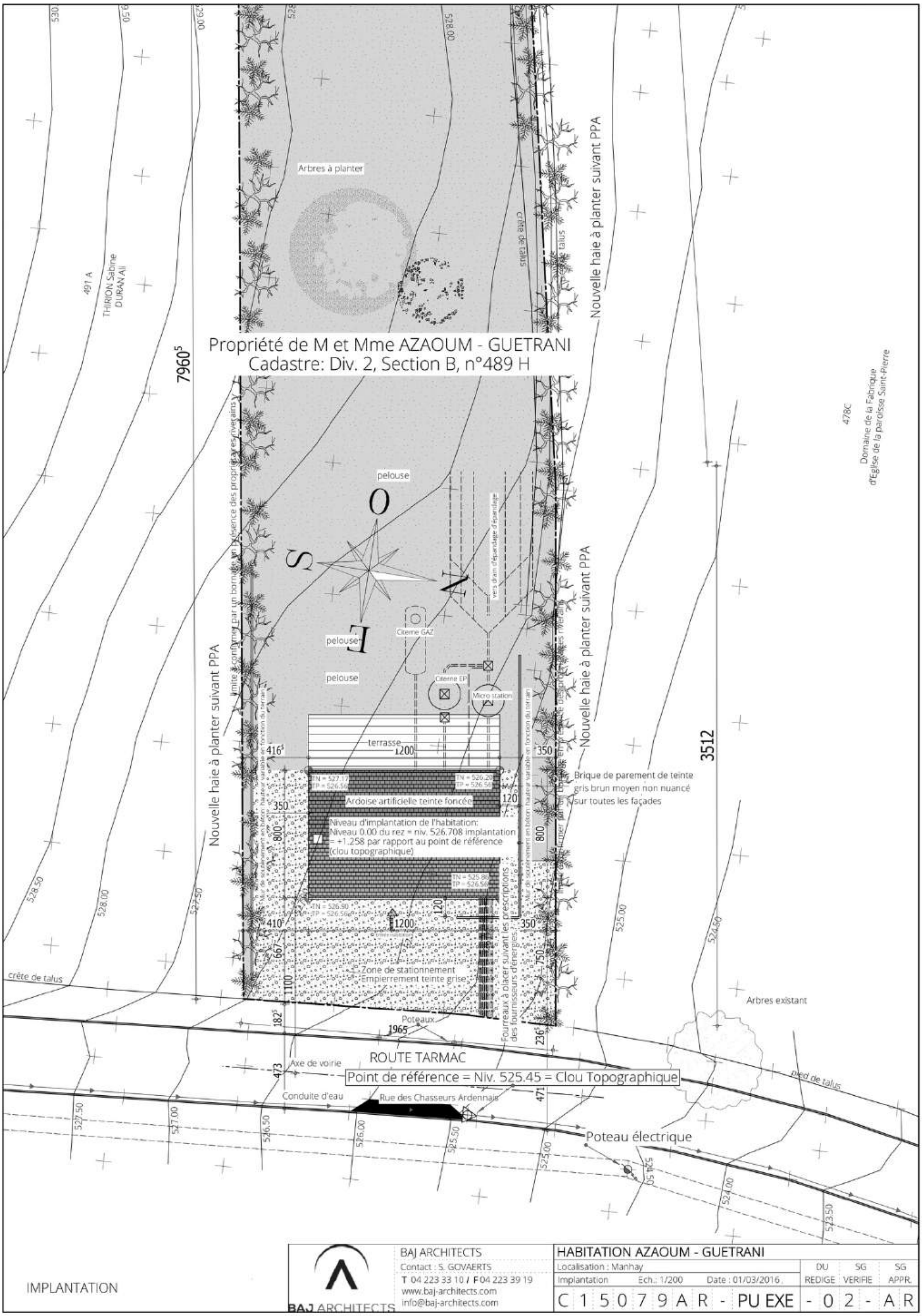

Arbres à planter
Propriété de M et Mme AZAOUM - GUETRANI
Cadastre: Div. 2, Section B, n°489 H
THIRION Sabine
DURAN Ali
491 A
7960⁵
478C
Domaine de la Fabrique d'Eglise de la paroisse Saint-Pierre
Nouvelle haie à planter suivant PPA
pelouse
O
S
N
E
Citerne GAZ
Citerne EP
Micro station
terrasse
1200
416⁵
350
Brique de parement de teinte gris brun moyen non nuancé sur toutes les façades
Ardoise artificielle teinte foncée
Niveau d'implantation de l'habitation:
Niveau 0.00 du rez = niv. 526.708 implantation = +1.258 par rapport au point de référence (clou topographique)
800
120
410
3512
Zone de stationnement
Empierrement teinte grise
Fourreaux à placer suivant les prescriptions des fournisseurs d'énergies
crête de talus
Arbres existant
Poteaux
1965
ROUTE TARMAC
Axe de voirie
Point de référence = Niv. 525.45 = Clou Topographique
pied de talus
Conduite d'eau
Rue des Chasseurs Ardennais
Poteau électrique
IMPLANTATION
BAJ ARCHITECTS
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info@baj-architects.com
HABITATION AZAOUM - GUETRANI
Localisation : Manhay
Implantation Ech.: 1/200 Date : 01/03/2016
DU REDIGE
SG VERIFIE
SG APPR.
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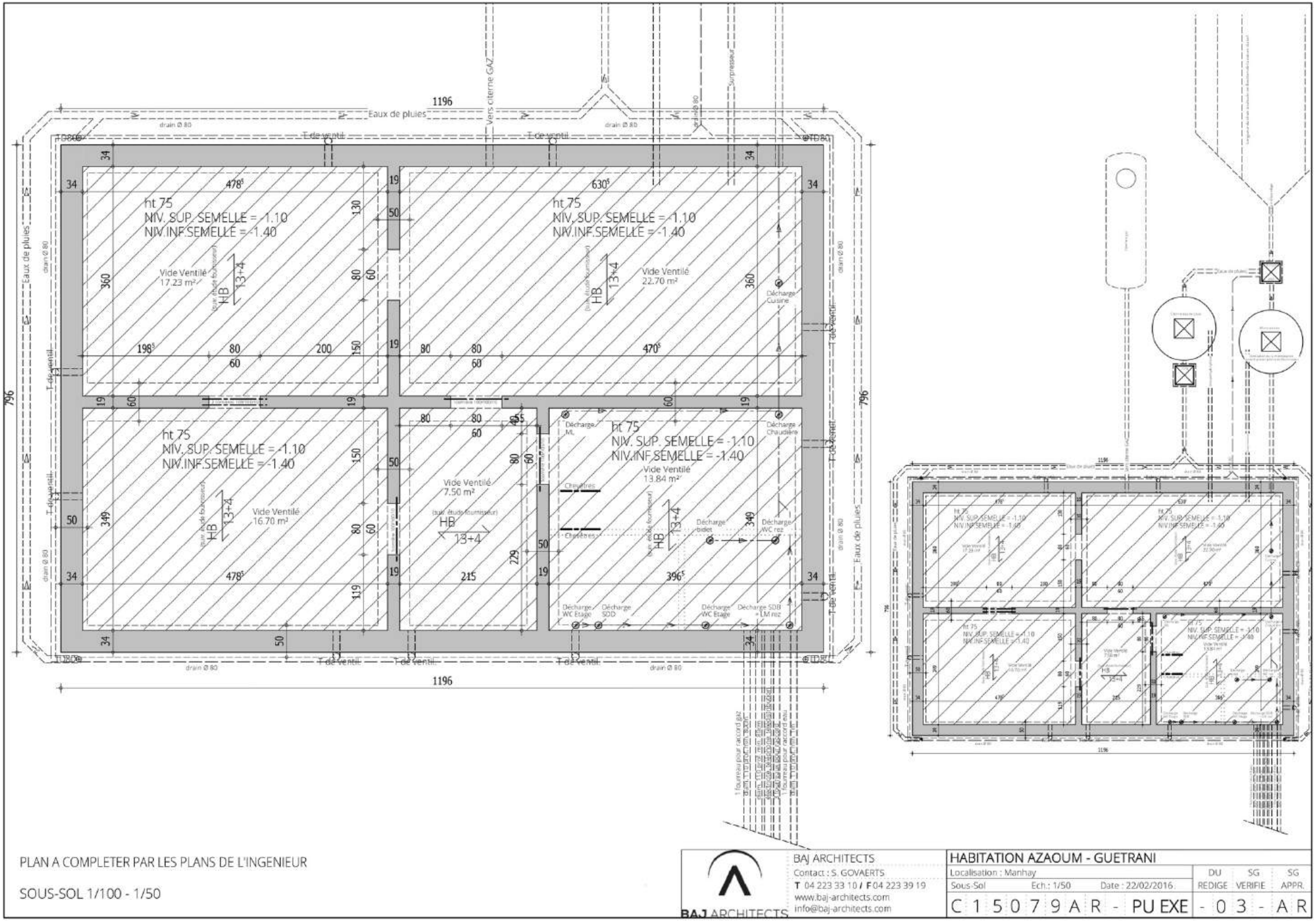
1196
Eaux de pluies
Vers citerne GAZ
Surpresseur
drain Ø 80
T de ventil
796
ht 75
NIV. SUP. SEMELLE = -1.10
NIV.INF.SEMELLE = -1.40
Vide Ventilé
17.23 m²
22.70 m²
16.70 m²
7.50 m²
13.84 m²
HB
13+4
Décharge Cuisine
Décharge ML
Décharge Chaudière
Chevêtres
Décharge bidet
Décharge WC rez
Décharge WC Etage
Décharge SDD
Décharge SDB + LM rez
PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR
SOUS-SOL 1/100 - 1/50
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Sous-Sol
Ech.: 1/50
Date : 22/02/2016
DU
SG
SG
REDIGE
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APPR.
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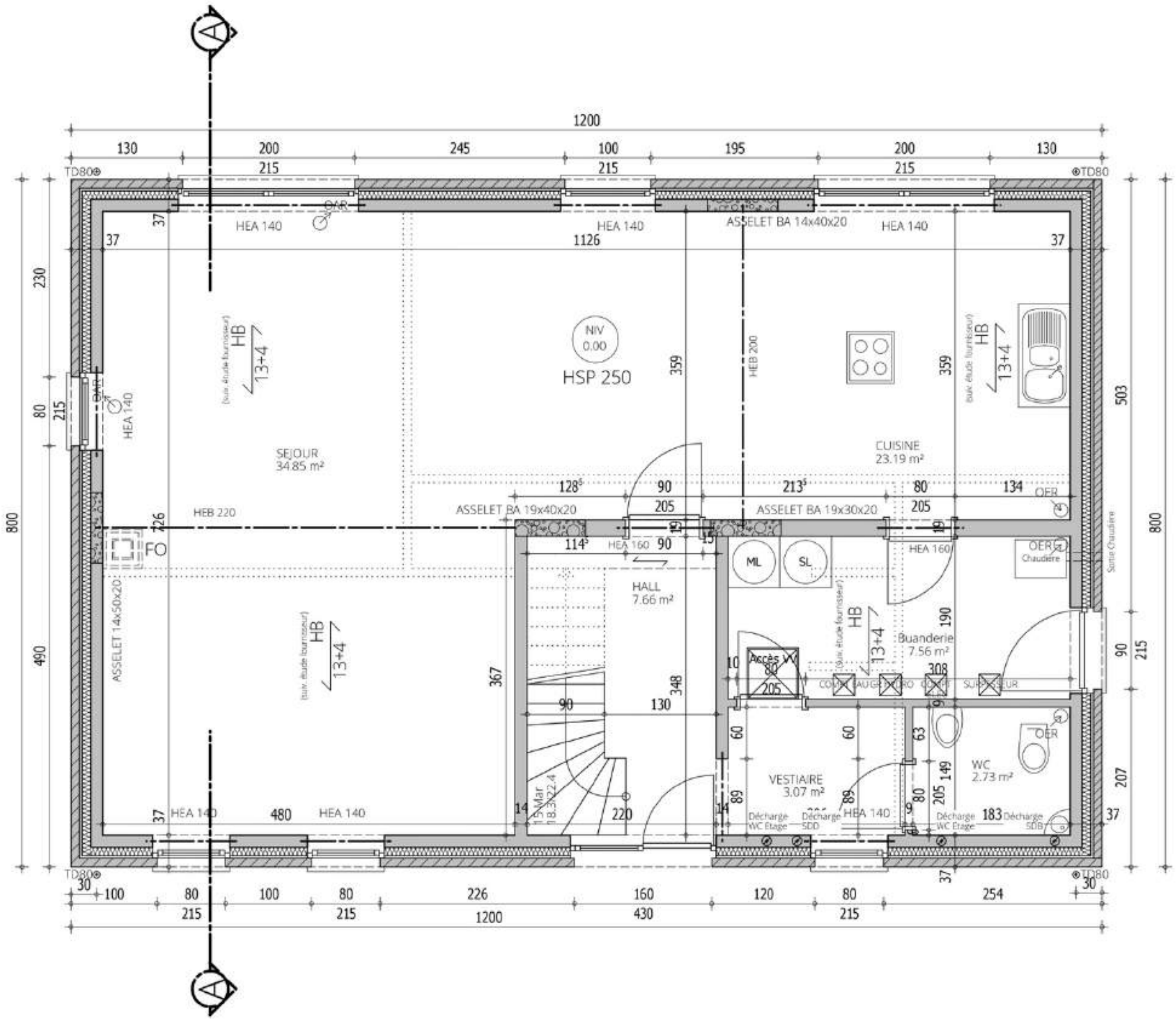

PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR

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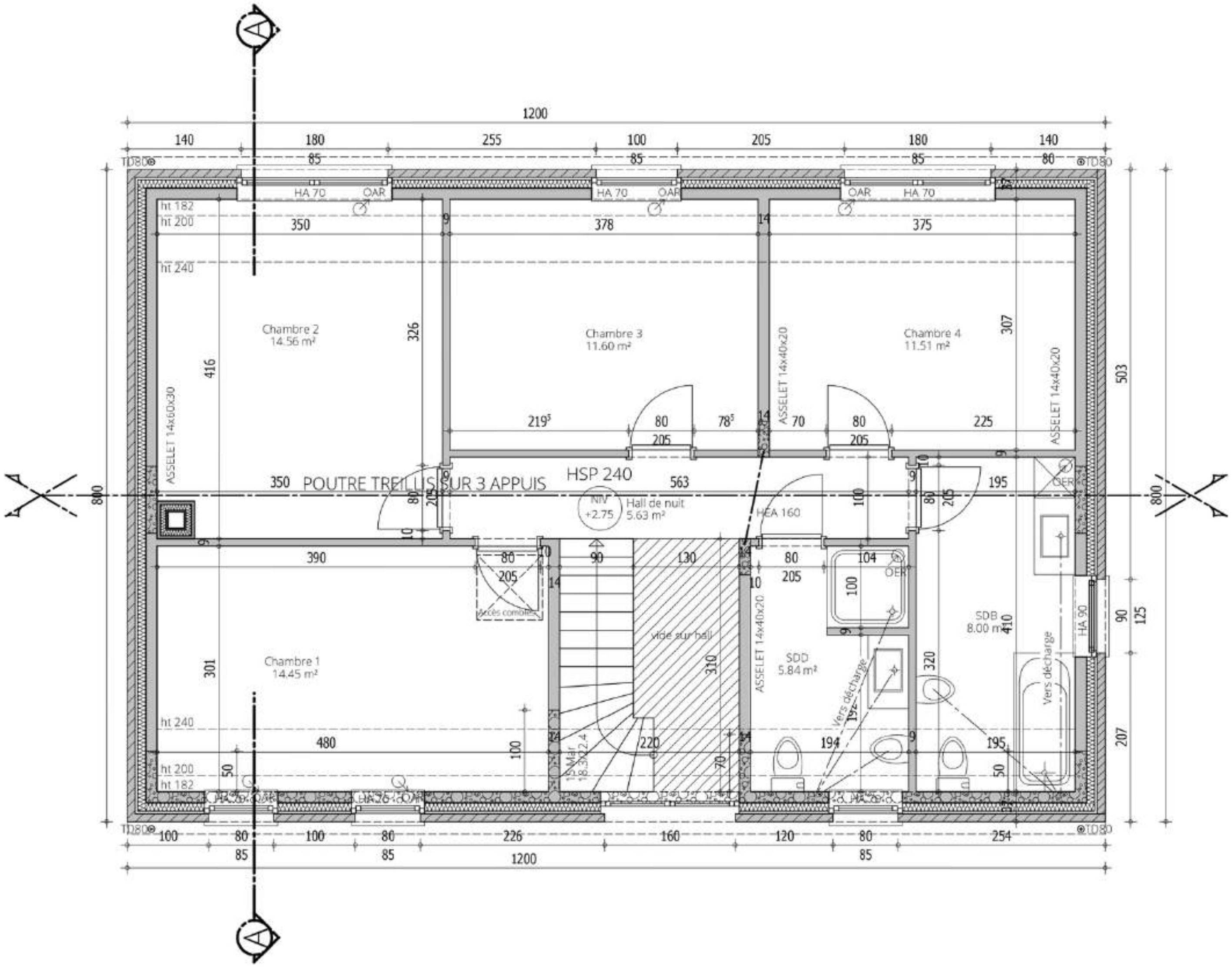

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HABITATION AZAOUM - GUETRANI				DU	SG	SG
Localisation : Manhay						
Etage	Ech.: 1/50	Date : 22/02/2016		REDIGE	VERIFIE	APPR.
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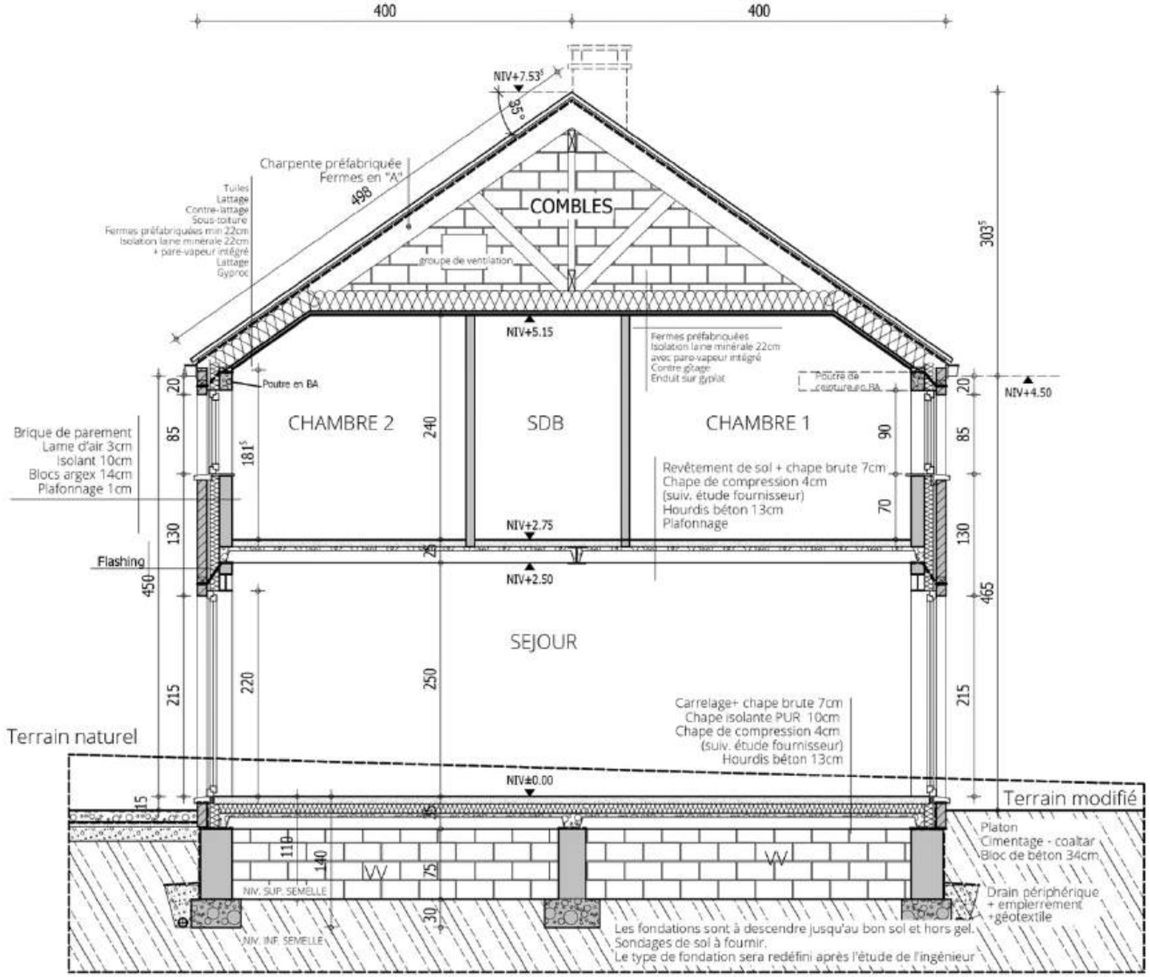

PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR

COUPE AA

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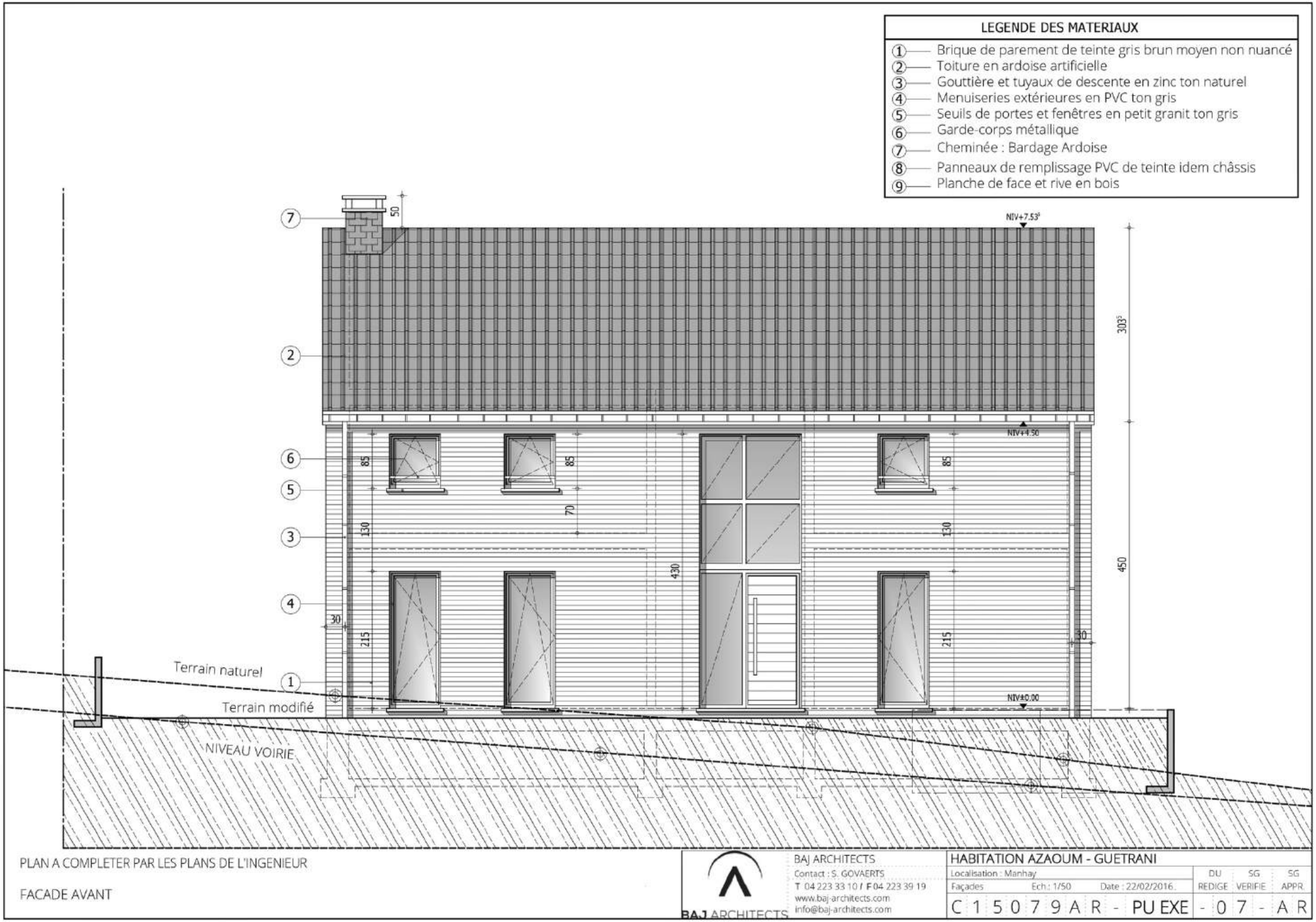
LEGENDE DES MATERIAUX
1 Brique de parement de teinte gris brun moyen non nuancé
2 Toiture en ardoise artificielle
3 Gouttière et tuyaux de descente en zinc ton naturel
4 Menuiseries extérieures en PVC ton gris
5 Seuils de portes et fenêtres en petit granit ton gris
6 Garde-corps métallique
7 Cheminée : Bardage Ardoise
8 Panneaux de remplissage PVC de teinte idem châssis
9 Planche de face et rive en bois
NIV+7.53
NIV+4.50
NIV±0.00
Terrain naturel
Terrain modifié
NIVEAU VOIRIE
PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR
FACADE AVANT
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Façades
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Date : 22/02/2016
DU REDIGE
SG VERIFIE
SG APPR
C15079AR - PU EXE - 07 - AR

LEGENDE DES MATERIAUX

1. Brique de parement de teinte gris brun moyen non nuancé
2. Toiture en ardoise artificielle
3. Gouttière et tuyaux de descente en zinc ton naturel
4. Menuiseries extérieures en PVC ton gris
5. Seuils de portes et fenêtres en petit granit ton gris
6. Garde-corps métallique
7. Cheminée : Bardage Ardoise
8. Panneaux de remplissage PVC de teinte idem châssis
9. Planche de face et rive en bois

PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR

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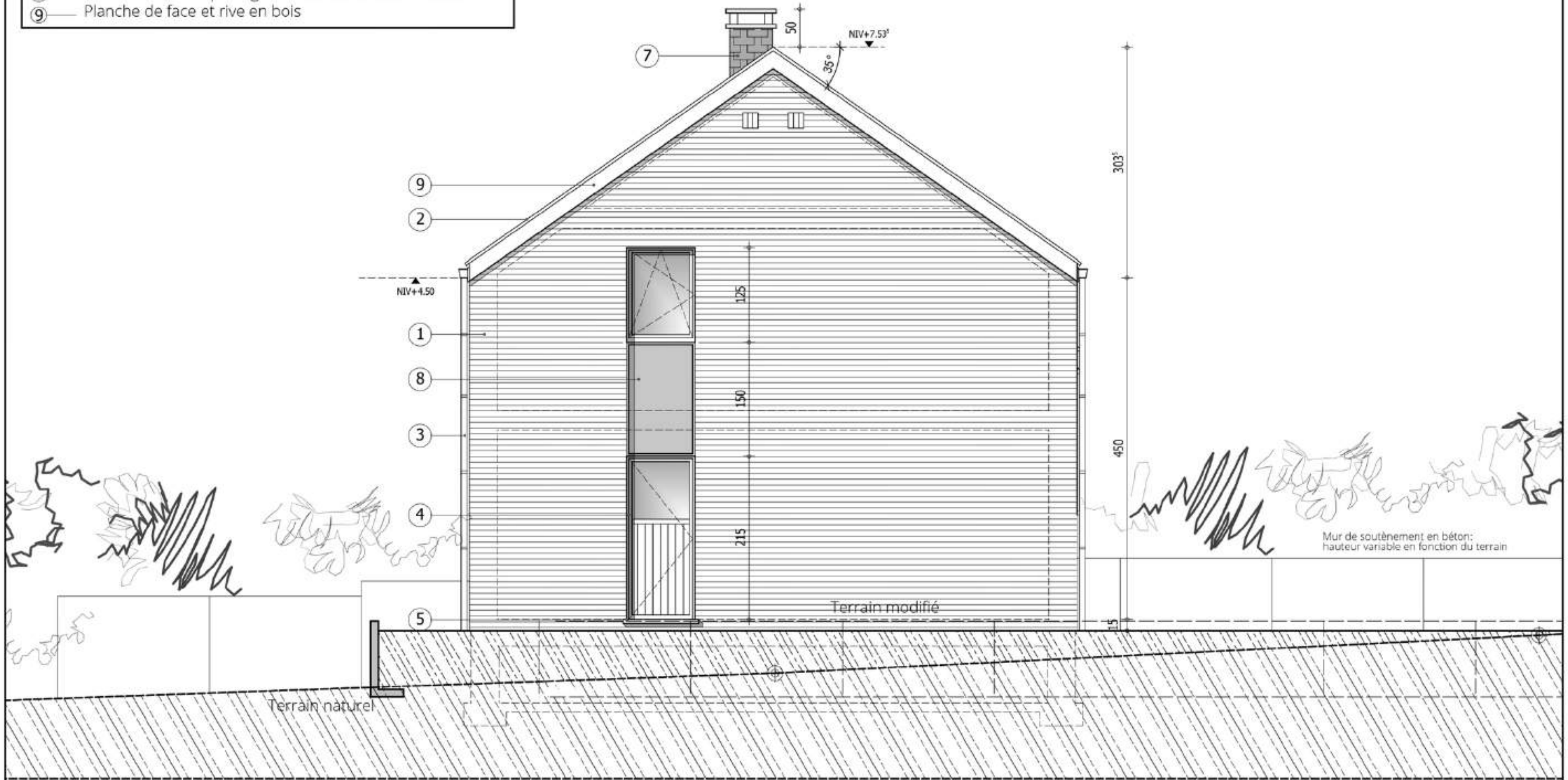
C 1 5 0 7 9 A R - PU EXE - 0 8 - A R			

LEGENDE DES MATERIAUX
(1) Brique de parement de teinte gris brun moyen non nuancé
(2) Toiture en ardoise artificielle
(3) Gouttière et tuyaux de descente en zinc ton naturel
(4) Menuiseries extérieures en PVC ton gris
(5) Seuils de portes et fenêtres en petit granit ton gris
(6) Garde-corps métallique
(7) Cheminée : Bardage Ardoise
(8) Panneaux de remplissage PVC de teinte idem châssis
(9) Planche de face et rive en bois



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Façades	Ech.: 1/50	Date : 22/02/2016.	REDIGE	VERIFIE	APPR.

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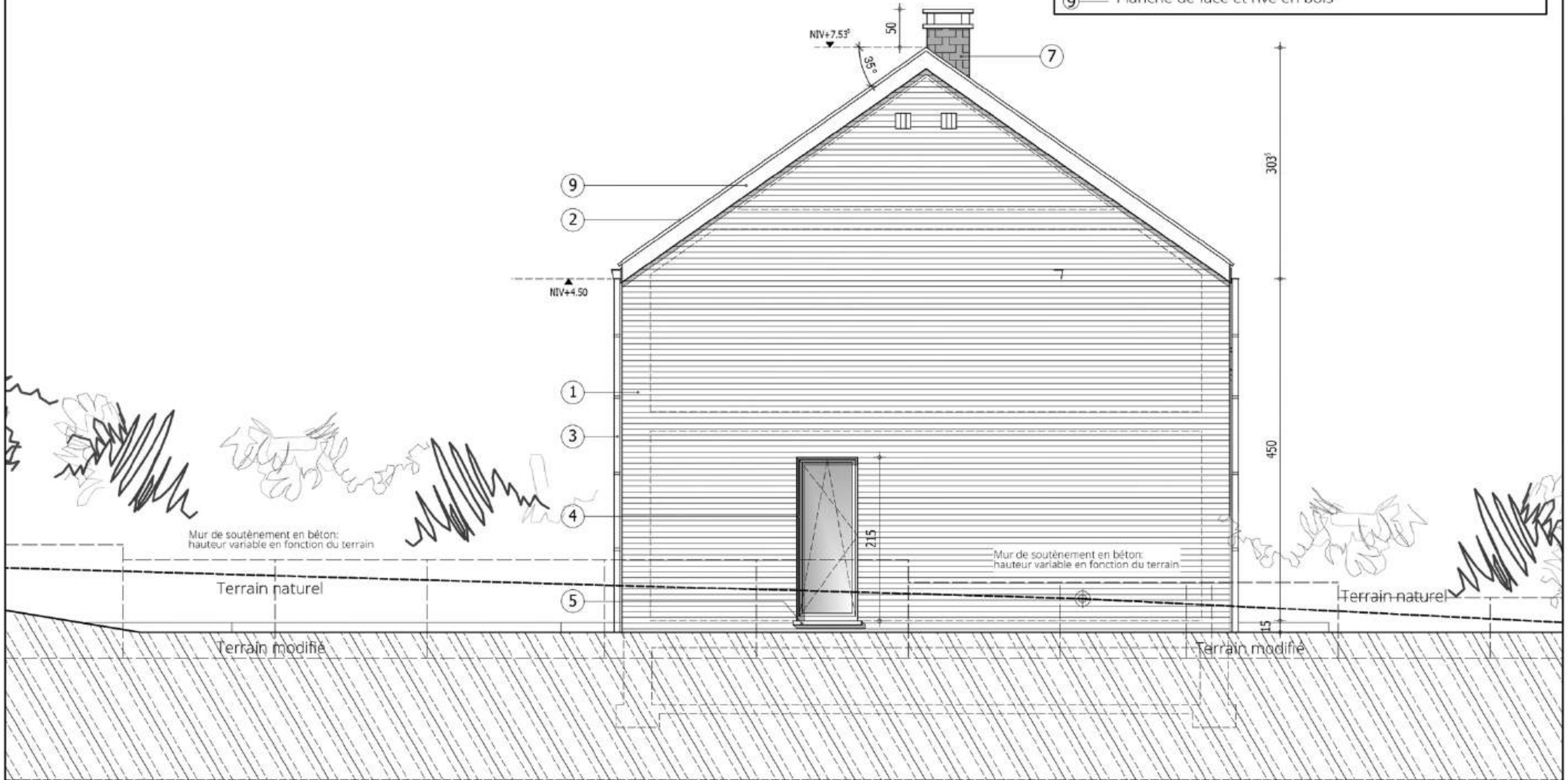
LEGENDE DES MATERIAUX

1. Brique de parement de teinte gris brun moyen non nuancé
2. Toiture en ardoise artificielle
3. Gouttière et tuyaux de descente en zinc ton naturel
4. Menuiseries extérieures en PVC ton gris
5. Seuils de portes et fenêtres en petit granit ton gris
6. Garde-corps métallique
7. Cheminée : Bardage Ardoise
8. Panneaux de remplissage PVC de teinte idem châssis
9. Planche de face et rive en bois



PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR

FACADE LATERALE GAUCHE

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Façades	Ech.: 1/50	Date : 22/02/2016	REDIGE	VERIFIE	APPR.
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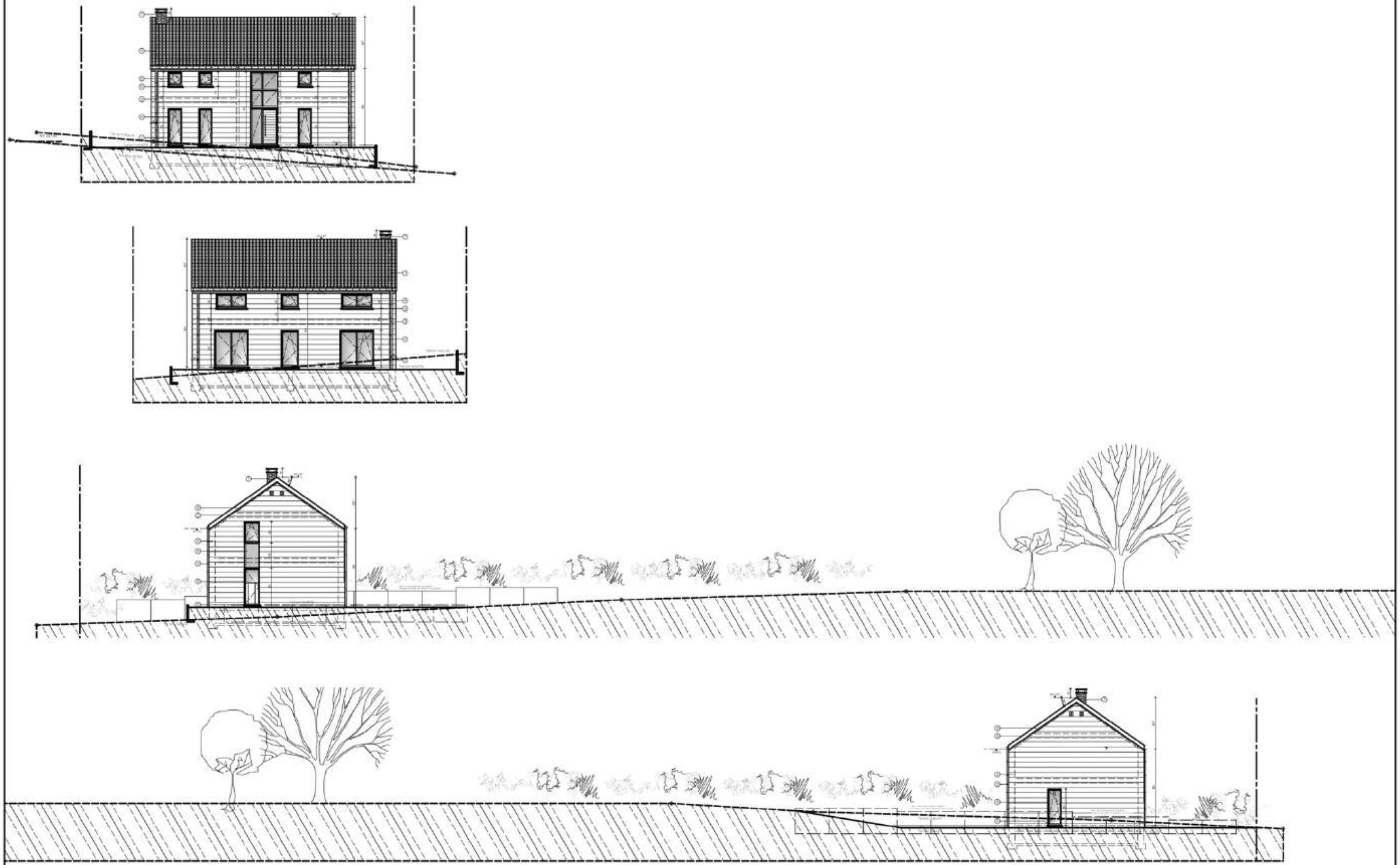

PLAN A COMPLETER PAR LES PLANS DE L'INGENIEUR

PROFILS

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BAJ ARCHITECTS

Annex 2 : Manhay house's bill of quantity

AZAOUM-GUETRANI METRE DEFINITIF Préparé par VG, le 1/07/16

TERRASSEMENT	Unit	Qt
Terrassement - terres sur place (estimation)	m3	185,00
Empierrement accès camions (recul < 8 mct)	fft	1,00
Empierrement accès camions (tranche 8 mct complémentaire)	fft	1,00
Nivellement 1 journée 8h	fft	1,00
Mini Station d'Epuration (1/5 EH, type agréée)	pce	1,00
Tranchée filtrante 0,5/40 mct (3 bras)	pce	1,00
Citerne à eau de pluie 5 000 L	pce	1,00
Pré-filtre pour eau de pluie	pce	1,00
TOTAL:		

For.2.1/1/06-Rev. 00-15/06/01-

Source : Maisons Blaviers

MACONNERIE	**Unit**	**Qt**
Implantation du bâtiment	fft	1,00
Fondations spéciales de type semelles armées avec v.v. suivant étude du bureau d'ingénieurs	rem	1,00
LACASSE-MONFORT SPRL du 09/02/2016 : selon le détail ci annexé	rem	1,00
Eléments structuraux suivant étude du bureau d'ingénieurs LACASSE-MONFORT SPRL	rem	1,00
du 09/02/2016 : selon le détail ci annexé	rem	1,00
CV 60/60 double couvercle fonte : niveau et raccord pour appareil d'égouttage	pce	1,00
Rem. : MINI STATION D'EPURATION :	rem	1,00
Rem. : Nombre et dimensions, chambre(s) de visite, à adapter selon marque, voir conducteur	rem	1,00
CV 60/60 double couvercle fonte : niveau et DOUBLE raccord pour citerne à eau de pluie	pce	1,00
CV 60/60 double couvercle fonte : niveau et raccord pour pré-filtre	pce	1,00
CV 60/60 double couvercle fonte : niveau et raccord pour répartition	pce	1,00
Installation de chantier	fft	1,00
Boucle de terre : câble de cuivre	mct	45,00
Drain périphérique coffrant avec gravier et bidim	mct	40,48
Manchon pour eau, électricité, téléphone, tv, mazout/gaz	pce	5,00
Canalisation 110	mct	74,40
Arrivée : chaudière à condensation	inc	1,00
Saignée, pose, ragréage canalisations vers étage	pce	4,00
Cimentage + coaltar + platon sur murs caves et/ou vides ventilés contre terres	m2	40,00
Blocs de béton lourd sous-sol, ép. 34 cm	m3	13,09
Blocs de béton lourd sous-sol, ép. 19 cm	m3	4,16
Ventilation cave et/ou vide-ventilé	pce	10,00
Maçonnerie d'élévation argile exp. 14 (type argex) + brique de parement	m3	60,98
Diba (en continu)	fft	1,00
Acier galvanisé pour cornière : ancrages necessaire inclus	kg	266,40
Isolation polyuréthane ép. 10 cm	m2	196,71
Déd. brique de parement pour panneau de menuiserie	m2	1,35
Hourdis (350 kg/m2)	m2	161,90
Aménagement : accès aux vides ventilés (béton + blocs) 50/50 pour taque 60/60	pce	1,00
Chape de compression : 4 cm	m2	161,90
Chape de compression : suppl. pour treillis	m2	161,90
Blocs d'argile expansé, en rez :	**rem**	**1,00**
Blocs d'argile expansé ép. 9 (type argex)	m2	11,38
Blocs d'argile expansé ép. 14 (type argex)	m3	2,28
Blocs d'argile expansé ép. 19 (type argex)	m3	2,64
Blocs d'argile expansé, à l'étage :	**rem**	**1,00**
Blocs d'argile expansé ép. 9 (type argex)	m2	48,99
Blocs d'argile expansé ép. 14 (type argex)	m3	3,28
Linteaux Stalton ou béton pour mur ép. 9	mct	9,60
Blocs de béton cellulaire, type blocs d'assise Ytong C4/500 ou équivalent :	**rem**	**1,00**
- interposition 1 tas en pieds de murs intérieurs : ép. 15, pour maçonnerie d'élévation	mct	37,60
- interposition 1 tas en pieds de murs intérieurs : ép. 10	mct	5,47
- interposition 1 tas en pieds de murs intérieurs : ép. 15	mct	6,07
- interposition 1 tas en pieds de murs intérieurs : ép. 20	mct	6,46
Rem. : au niveau de l'isolation du sol	rem	1,00
Isolation : polyuréthane, ép. idem murs ext. : sur la maçonnerie de pignon	mct	19,54
Cheminée : boisseau terre cuite 20/20	mct	5,50
Cheminée : manteau intérieur	m3	0,64
Cheminée : souche destinée à être ardoisée	m3	0,24
Cheminée : dalle de couverture avec aspirateur de fumée : 3 éléments	pce	1,00
Pierre de taille déb. ép. 5 cm pour baies sans talon	mct	16,50
Pierre de taille déb. ép. 5 cm pour baies avec talon (p. entrée et/ou p. service)	mct	2,70
TOTAL:		

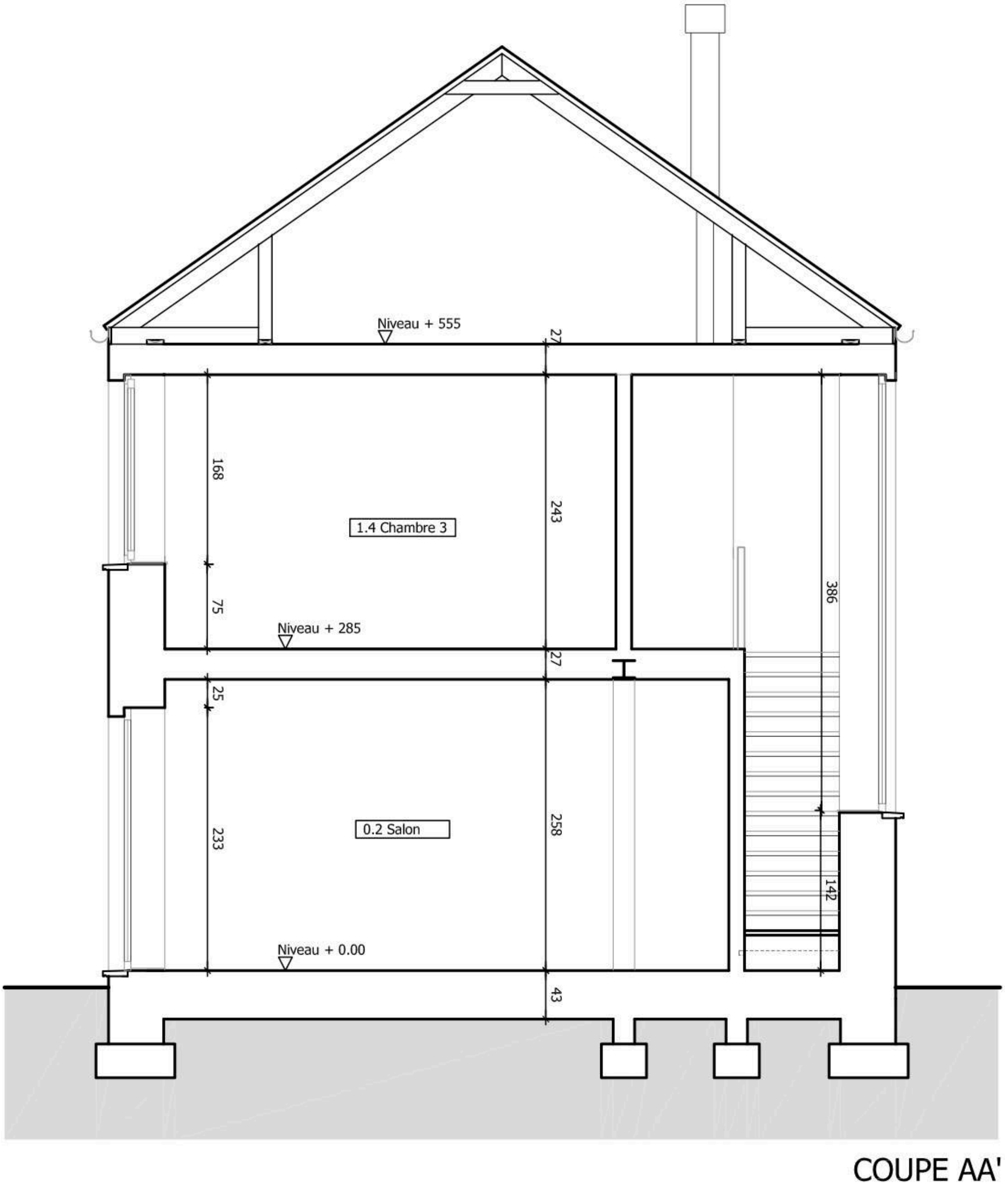
CHARPENTE	Unit	Qt
Hauteur sous corniche du volume principal :	mct	4,50
(par rapport au niveau rez fini)	rem	1,00
Rem. : section charpente y compris entrait à adapter à isolation 22 cm + lame d'air de 2cm	rem	1,00
Charpente préfabriquée : type A : comble perdu sur entrait non porteur	**rem**	**1,00**
Charpente en "A" : structure par fermette	pce	21,00
Charpente en "A" : poutres de faîtage	mct	11,54
Charpente préfabriquée : pour toiture à 2 versants	**nbr**	**1,00**
Angle 35° portée 8 mct >= 7,60 < 8,60	pce	21,00
Charpente préfabriquée : généralités	rem	1,00
Costières et rives en SRN traité	inc	1,00
Trémie pour accès combles 80/80 cm	pce	1,00
TOTAL:		

MENUISERIE EXT	Unit	Qt
MENUISERIE EXTERIEURE PVC BLANC : double vitrage Ug = 1,1 W/m2K :	**rem**	**1,00**
Suppl. pour châssis : PVC : couleur structuré ext./blanc int.	%s	1,00
Application des normes en vigueur en matière de ventilation NBN D50-001 : prix à détailler	rem	1,00
Vitrage sécurité en application de la norme NBN S23-002 : prix à détailler	rem	1,00
Isolation en mousse polyuréthane en pourtour de menuiserie : prix à détailler	rem	1,00
Menuiserie ext. : panneaux et habillages conforme aux normes en vigueur (Umax d'application)	rem	1,00
Ventilation par grilles intégrées type INVISIVENT dans la menuiserie cfr. au document ci-joint	inc	1,00
Porte d'entrée pleine 90/215 avec planchéiage (incl. kaltefeind et poignée)	pce	1,00
Porte de service demi vitrée 90/215 avec planchéiage (incl. kaltefeind)	pce	1,00
Portes: Kältefeind et poignée porte d'entrée	inc	1,00
Châssis extérieurs, double vitrage et quinc. :	**rem**	**1,00**
1 ouvrant : OB 80/85	pce	3,00
1 ouvrant : OB 90/125	pce	1,00
1 ouvrant : OB 100/85	pce	1,00
2 ouvrants : OS + OB 180/85	pce	2,00
Porte-fenêtre : 1 ouvrant : OB 80/215	pce	4,00
Porte-fenêtre : 1 ouvrant : OB 100/215	pce	1,00
Porte-fenêtre : 2 ouvrants : OS + OB 200/215	pce	2,00
1 fixe rect. 70/107,5	pce	2,00
1 fixe rect. 70/215	pce	1,00
1 fixe rect. 90/107,5	pce	2,00
1 fixe rect. en panneau lisse 90/150	pce	1,00
Renfort châssis (pour châssis composés)	mct	9,30
Garde-corps extérieurs : non compris	rem	1,00
TOTAL:		

PLAFONNAGE	Unit	Qt
Plafonnage sur murs (inclus buanderie)	m2	407,55
Plafonnage sur hourdis (inclus buanderie)	m2	72,25
Plafonnage sur plaques	m2	87,83
Tablettes : pose au mortier	pce	7,00
Plafonnage poutrelle : inhibiteur de rouille	inc	1,00
TOTAL:		
TABLETTES (FO)	**Unit**	**Qt**
Tablettes : fourniture marbre beige (Moka)	m2	1,55
TOTAL:		

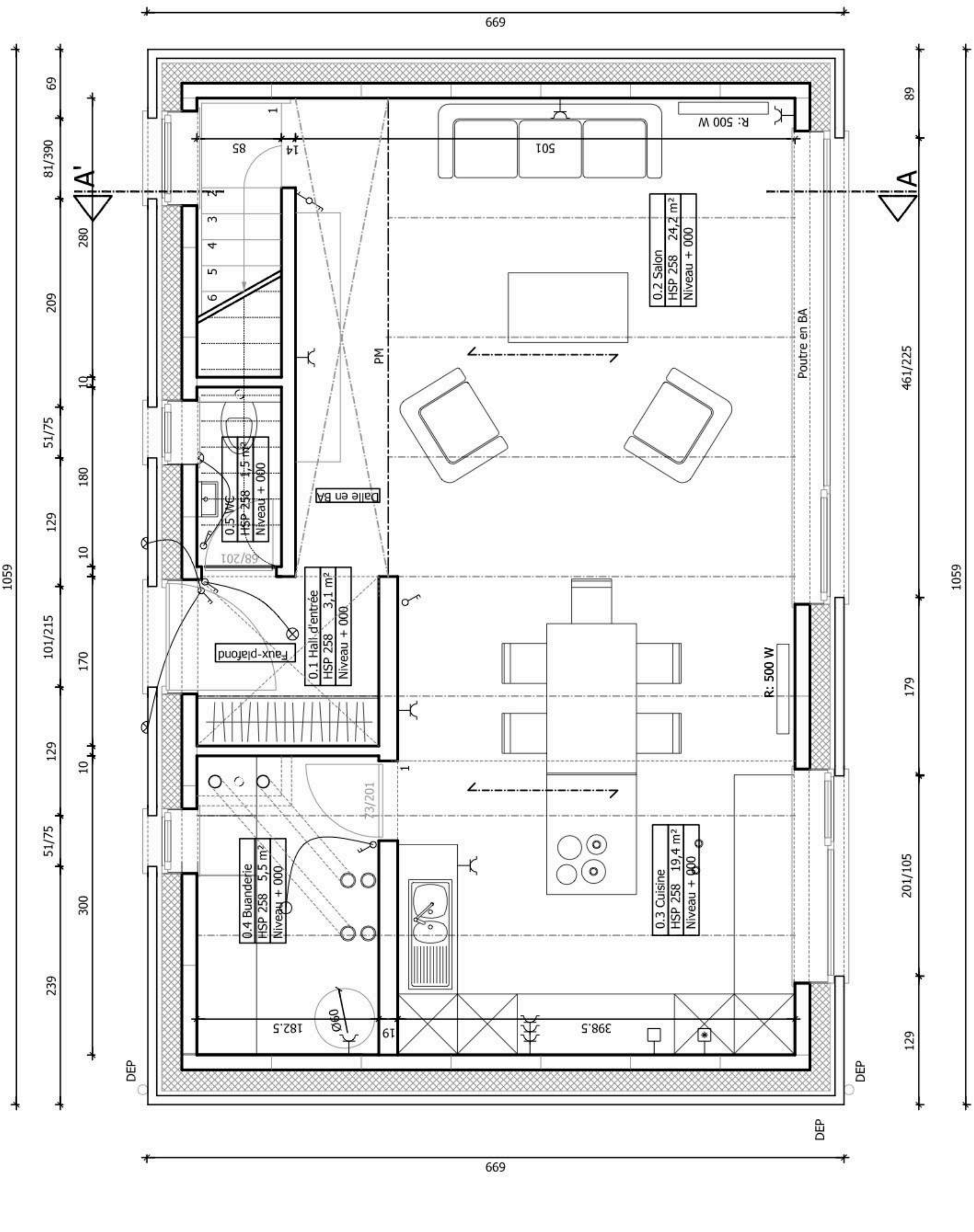
TERRASSEMENT	Unit	Qt
Terrassement - terres sur place (estimation)	m3	185,00
Empierrement accès camions (recul < 8 mct)	fft	1,00
Empierrement accès camions (tranche 8 mct complémentaire)	fft	1,00
Nivellement 1 journée 8h	fft	1,00
Mini Station d'Epuration (1/5 EH, type agréée)	pce	1,00
Tranchée filtrante 0,5/40 mct (3 bras)	pce	1,00
Citerne à eau de pluie 5 000 L	pce	1,00
Pré-filtre pour eau de pluie	pce	1,00
TOTAL:		

MENUISERIE INT	**Unit**	**Qt**
Porte simple tubulaire, MDF, prépeinte	pce	10,00
	-	
ESCALIER EN HETRE : avec rampe ou main courante :	**rem**	**1,00**
Escalier d'étage : 1/4 tournant, ACM simple face ou SCM double face	mche	15,00
Garde-corps	mct	1,30
Protection escalier	pce	1,00
Placement escalier d'étage	fft	1,00
	-	
Accès aux combles pour trémie 80/80 cm	pce	1,00
TOTAL:		



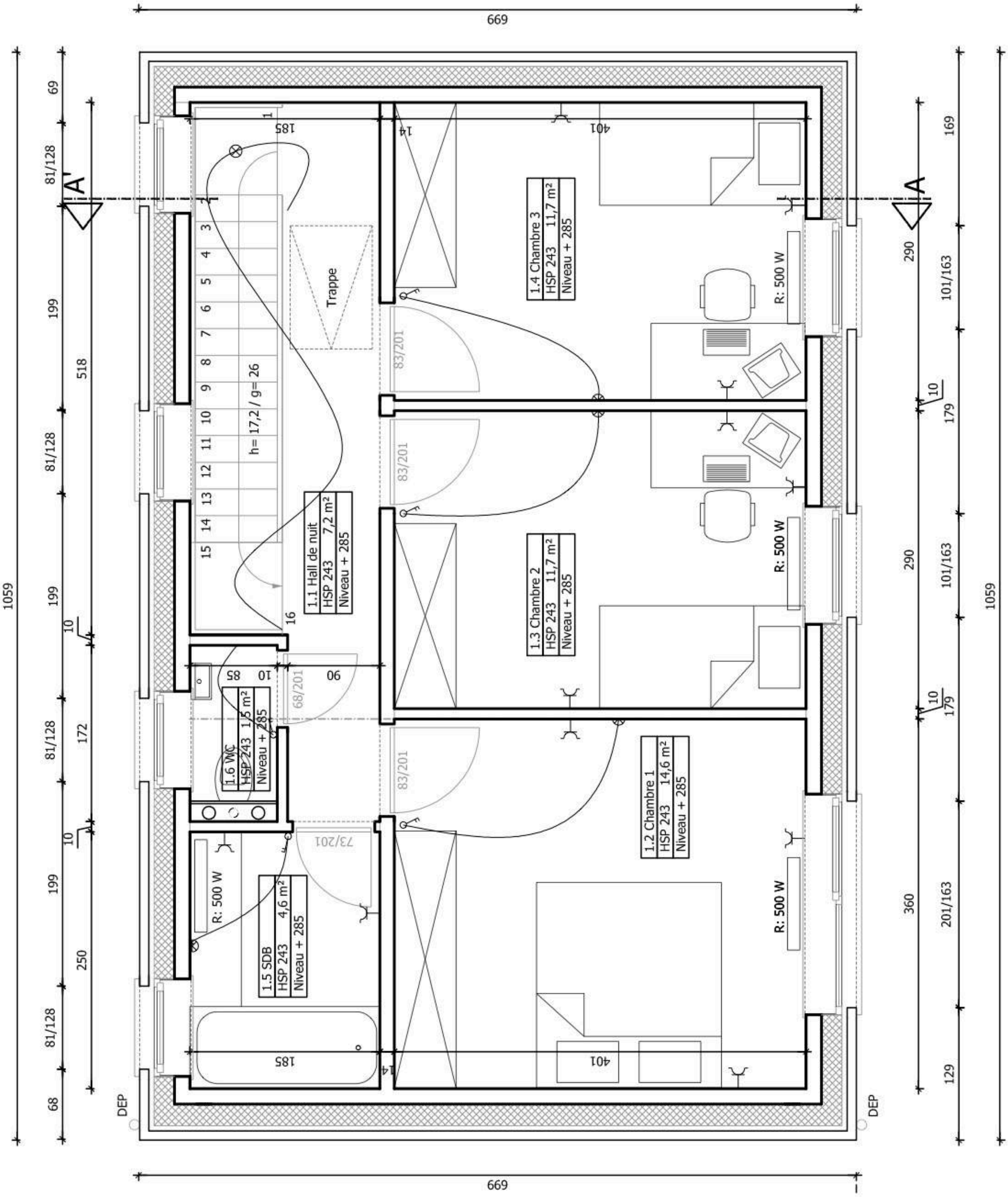
Source : CSTC - OptiCost

REZ



669
1059
A
A'
0.1 Hall d'entrée
HSP 258 3,1 m²
Niveau + 000
0.2 Salon
HSP 258 24,2 m²
Niveau + 000
0.3 Cuisine
HSP 258 19,4 m²
Niveau + 000
0.4 Buanderie
HSP 258 5,5 m²
Niveau + 000
0.5 WC
HSP 258 1,5 m²
Niveau + 000
Dalle en BA
Faux-plafond
Poutre en BA
PM
R: 500 W
501
398,5
182,5
85
14
19
Ø60
68/201
73/201
DEP
69
81/390
209
51/75
129
101/215
239
280
10
180
170
300
89
461/225
179
201/105

ETAGE


1.1 Hall de nuit
HSP 243 7,2 m²
Niveau + 285
1.2 Chambre 1
HSP 243 14,6 m²
Niveau + 285
1.3 Chambre 2
HSP 243 11,7 m²
Niveau + 285
1.4 Chambre 3
HSP 243 11,7 m²
Niveau + 285
1.5 SDB
HSP 243 4,6 m²
Niveau + 285
1.6 WC
HSP 243 1,5 m²
Niveau + 285
Trappe
h= 17,2 / g= 26
R: 500 W
A
A'
DEP
669
1059

OPTICOST - Cas de référence " Logements individuels 4F, 3F, 2F"

sur base du CSC Version 02/12/2015

METRE RECAPITULATIF										METRE DETAILLE						
Composant constructif (cfr Grille analyse)	n° article / poste	Désignation	NM	Quantité			U	PU	Total	Nb	Long	Larg	Haut	Fact		Total
				Logement 4F	Logement 3F	Logement 2F										
	2	**T2 Eléments de structures**														
	21	**Eléments de structures en maçonnerie**														
	21.1	Maçonneries portantes														
	21.12	Maçonneries portantes en blocs														
	21.12.2	Maçonneries portantes en blocs de béton pour murs en contact direct avec la terre														
Fondations	21.12.2b	Blocs de béton creux à perforations verticales														
		Blocs de béton creux enterrés largeur								2	6	0,5	0,21			1,26
		Blocs de béton creux enterrés longueur								2	10,6	0,5	0,21			2,226
		Blocs de béton creux enterrés longueur intérieure								1	9,6	0,2	0,21			0,4032
		Blocs de béton creux enterrés épaisseur 19 cm (mur extérieur)														
	21.12.2b.01	**Total blocs de béton creux**	QF	3,8892			m³									
	21.12.4	Maçonneries portantes en blocs de béton cellulaire														
Fondations	21.12.4a	Maçonneries portantes en blocs de béton cellulaire														
		bloc cellulaire longueur mur extérieur (ép=14cm)								2	9,9					19,8
		bloc cellulaire largeur mur mextérieur (ép=14cm)								2	6,7					13,4
		bloc cellulaire mur intérieur escalier(ép=14cm)								1	4,8					4,8
		bloc cellulaire mur intérieur entre buanderie et cuisine (ép=19cm)								1	4,8					4,8
	21.12.4a.01	**Total bloc cellulaire (ép=14cm)**	QF	38			m									
	21.12.4a.02	**Total bloc cellulaire (ép=19cm)**	QF	4,8			m									
	21.12.7	Maçonneries portantes en blocs d'argile expansée														
Murs ext. façade	21.12.7a	Blocs d'argile expansée extérieur 14cm														
		façade avant rez-de-chaussée								1	9,9	2,9	0,14			28,71
		façade avant étage								1	9,9	2,82	0,14			27,92
		façade arrière rez-de-chaussée								1	9,9	2,9	0,14			28,71
		façade arrière étage								1	9,9	2,82	0,14			27,92
		pignon rez-de-chaussée 1								1	6	2,9	0,14			17,40
		pignon rez-de-chaussée 2								1	6	2,9	0,14			17,40
		pignon étage 1								1	6	2,82	0,14			16,92
		pignon étage 2								1	6	2,82	0,14			16,92
		pignon triangle 1								1						1,13
		pignon triangle 2								1						1,13
		déduction porte d'entrée façade avant								-1	1,21	2,18	0,14			-2,64
		déduction fenêtre fixe façade avant								-1	1,01	3,95	0,14			-3,99
		déduction fenêtres rez-de-chaussée façade avant								-2	0,71	0,8	0,14			-1,14
		déduction fenêtres étage façade avant								-3	1,01	1,33	0,14			-4,03
		déduction ensemble porte-fenêtre fixe rez-de-chaussée façade arrière								-1	4,81	2,3	0,14			-11,06
		déduction ensemble fenêtre rez-de-chaussée façade arrière								-1	2,21	1,1	0,14			-2,43
		déduction double fenêtre étage façade avant								-1	2,21	1,68	0,14			-3,71
		déduction fenêtres étage façade arrière								-2	1,21	1,68	0,14			-4,07
	21.12.7a.01	**Total blocs d'argile expansée extérieur 14 cm**	QP	151,09			m³									
		Blocs d'argile expansée 14 cm entre escalier et living								1	3,9	2,58	0,14			1,41
		Blocs d'argile expansée 14 cm entre hall, SDB et chambres								1	9,6	2,3	0,19			4,20
	21.12.7a.02	**Total blocs d'argile expansée intérieur 14 cm**	QP	5,60			m³									
		Blocs d'argile expansée 19 cm entre buanderie et cuisine et entre hall et living								1	4,6	2,58	0,19			2,25

sur base du CSC Version 02/12/2015

METRE RECAPITULATIF								METRE DETAILLE						
Composant constructif (cfr Grille analyse)	n° article / poste	Désignation	NM	Quantité	U	PU	Total	Nb	Long	Larg	Haut	Fact		Total
		déduction porte						-1	0,8	2,01	0,19			-0,31
		déduction portes						-3	0,9	2,01	0,19			-1,03
	21.12.7a.03	**Total blocs d'argile expansée interieur 19 cm**	**QP**	**0,92**	**m³**									
	21.2	Maçonneries non portantes												
	21.22	Maçonneries non portantes en blocs												
	21.22.5	Maçonneries non portantes en blocs d'argile expansée												
Cloisons int.	21.22.5a	Blocs d'argile expansée												
		Blocs d'argile expansée 9 cm entre buanderie et hall						1	1,85	2,58				4,77
		Blocs d'argile expansée 9 cm entre WC et hall						1	0,85	2,58				2,19
		Blocs d'argile expansée 9 cm entre WC et escalier						1	0,85	2,58				2,19
		déduction portes						-1	0,75	2,01				-1,51
		Blocs d'argile expansée 9 cm entre SDB et hall/WC						1	1,85	2,53				4,68
		Blocs d'argile expansée 9 cm entre WC et escalier						1	0,85	2,53				2,15
		Blocs d'argile expansée 9 cm entre WC et hall						1	1,82	2,53				4,60
		Blocs d'argile expansée 9 cm entre chambres						2	4,05	2,53				20,49
		déduction portes						-2	0,75	2,01				-3,02
		déduction portes						-1	0,8	2,01				-1,61
	21.22.5a.01	**Total blocs d'argile expansée 9cm**	**QP**	**34,96**	**m²**									
	21.3	Maçonneries de parement												
	21.31	Maçonneries de parement en briques												
	21.31.1	Maçonneries de parement en briques de terre cuite moulée main												
Murs ext. façade	21.31.1a	Briques moulées à la main												
		briques façade avant rez-de-chaussée						1	10,6	2,9				30,74
		briques façade avant étage						1	10,6	2,82				29,89
		briques façade arrière rez-de-chaussée						1	10,6	2,9				30,74
		briques façade arrière étage						1	10,6	2,82				29,89
		briques pignons 1 rez-de-chaussée						1	7	2,9				20,30
		briques pignons 2 rez-de-chaussée						1	7	2,9				20,30
		briques pignons 1 étage						1	7	2,82				19,74
		briques pignons 2 étage						1	7	2,82				19,74
		briques pignons 1 triangle						1						8,07
		briques pignons 2 triangle						1						8,07
		déduction porte d'entrée façade avant						-1	1,01	2,15				-2,17
		déduction fenêtre fixe façade avant						-1	0,81	3,9				-3,16
		déduction fenêtres rez-de-chaussée façade avant						-2	0,51	0,75				-0,77
		déduction fenêtres étage façade avant						-3	0,51	0,75				-1,15
		déduction ensemble porte-fenêtre fixe rez-de-chaussée façade arrière						-1	4,61	2,25				-10,37
		déduction ensemble fenêtre rez-de-chaussée façade arrière						-1	2,01	1,05				-2,11
		déduction double fenêtre étage façade avant						-1	2,01	1,63				-3,28
		déduction fenêtres étage façade arrière						-2	1,01	1,63				-3,29
	21.31.1a.01	**Total briques**	**QF**	**191,18 143,07 94,97**	**m²**									
	21.35	Eléments particuliers de façades												
	21.35.1	Seuils												
Murs ext. façade	21.35.1a	Seuils en pierre												
		Seuils en pierre buanderie						1	0,61	0,25	0,05			0,01
		Seuils en pierre WC						1	0,61	0,25	0,05			0,01
		Seuils en pierre escalier						1	0,91	0,25	0,05			0,01
		Seuils en pierre cuisine						1	2,11	0,25	0,05			0,03
		Seuils en pierre chambre 1						1	2,11	0,25	0,05			0,03
		Seuils en pierre chambre 2						1	1,11	0,25	0,05			0,01
		Seuils en pierre chambre 3						1	1,11	0,25	0,05			0,01
		Seuils en pierre SDB						1	0,91	0,25	0,05			0,01

METRE RECAPITULATIF								METRE DETAILLE						
Composant constructif (cfr Grille analyse)	n° article / poste	Désignation	NM	Quantité	U	PU	Total	Nb	Long	Larg	Haut	Fact		Total
		Seuils en pierre WC						1	0,91	0,25	0,05			0,01
		Seuils en pierre escalier						1	0,91	0,25	0,05			0,01
		Seuils en pierre pour baie salon (+ porte-fenêtre						1	4,71	0,25	0,05			0,06
	21.35.1a.01	**Total seuils en pierre sans coussinet**	**QF**	**0,14**	**m³**									
	21.4	Eléments particuliers pour maçonneries												
	21.41	Armatures pour maçonneries												
	21.41.1	Armatures horizontales pour maçonneries												
Murs ext. façade	21.41.1b	Armatures horizontales préfabriquées à treillis pour maçonneries (barres plates)												
	21.41.1b.01	**Armatures comprises dans les maçonneries**	**PM**											
	22	**Eléments de structures en béton**												
	22.1	Eléments de structures en béton												
	22.11	Poutres en béton												
	22.11.1	Poutres en béton armé coulées sur place												
Murs ext. façade	22.11.1a	Poutres en béton armé coulées sur place												
		poutre au dessus de la baie du séjour en façade arrière						1	2,15					
	22.11.1a.01	**Total poutre BA**	**QP**	**2,15**	**m³**									
	22.13	Linteaux en béton												
	22.13.2	Linteaux préfabriqués en béton armé												
	22.13.2a	Linteaux creux préfabriqués en béton précontraint												
		linteaux sur blocs de 14 cm buanderie			m			1	0,51					0,51
		linteaux sur blocs de 14cm WC			m			1	0,51					0,51
		linteaux sur blocs de 14cm escalier			m			1	0,81					0,81
		linteaux sur blocs de 14 cmcuisine			m			1	2,01					2,01
		linteaux sur blocs de 14cm hall d'entrée			m			1	1,01					1,01
		linteaux sur blocs de 14cm living			m			1	4,61					4,61
		linteaux sur blocs de 14cm chambre 1			m			1	2,01					2,01
		linteaux sur blocs de 14cm chambre 2			m			1	1,01					1,01
		linteaux sur blocs de 14cm chambre 3			m			1	1,01					1,01
		linteaux sur blocs de 14cm SDB			m			1	0,81					0,81
		linteaux sur blocs de 14cm WC			m			1	0,81					0,81
		linteaux sur blocs de 14cm escalier			m			1	0,81					0,81
Murs ext. façade	**22.13.2a.01**	**Total linteaux fenêtres**	**PM**											
		linteaux sur blocs de 9cm portes WC 75x201			m			2	0,75					1,5
		linteaux sur blocs de 9cm porte SDB 80x201			m			1	0,8					0,8
		linteaux sur blocs de 14cm portes chambres 90x201			m			3	0,9					2,7
		linteaux sur blocs de 19cm porte buanderie 80x201			m			1	0,9					0,9
Murs intérieurs	**22.13.2a.02**	**Total linteau portes**	**PM**											
	22.15	Planchers en béton												
	22.15.1	Planchers en béton armé coulés sur place												
Planchers intérieurs	22.15.1a	Planchers en dalles pleines de béton armé coulées sur place												
		Planchers en dalles pleines de béton armé coulées sur place près de l'escalier						1	4,8	0,86	0,18			0,72
	22.15.1a.01	**Total dalle en BA**	**QF**	**0,72**	**m³**									
	22.15.2	Planchers à éléments préfabriqués en béton armé et précontraints												
Planchers intérieurs	22.15.2c	Planchers à dalles alvéolées en béton armé												
		Planchers à dalles alvéolées en béton armé y compris chape de compression						1	9,8	6,15				60,27
		déduction trémie escalier						-1	5,2	0,85				-4,42
		déduction dalle en BA (22.15.1a)						-1	4,8	0,86				-4,13
	22.15.2c.01	**Total hourdis**	**QF**	**51,72**	**m²**									
	22.4	Eléments particuliers en béton												
	22.42	Pièces d'appui en béton armé												

METRE RECAPITULATIF								METRE DETAILLE						
Composant constructif (cfr Grille analyse)	n° article / poste	Désignation	NM	Quantité	U	PU	Total	Nb	Long	Larg	Haut	Fact		Total
	22.42.1	Pièces d'appui en béton armé coulées sur place												
Planchers intérieurs	22.42.1a	Asselets en béton armé coulés sur place												
		asselet sur mur intérieur de 19cm						1	0,3	0,19	0,15			0,01
		asselet dans bloc porteur de contre façade de 14 cm						1	0,6	0,14	0,15			0,01
	22.42.1a.01	**Total asselets en béton armé coulés sur place**	QP	0,02	m³									
	23	**Eléments de structures en acier**												
	23.1	Eléments de structures en acier												
	23.11	Poutres en acier												
Planchers intérieurs	23.11.1a	Poutres en acier laminé												
		poutrelle métallique (à calculer par l'i						1	4,8					4,8
	23.11.1a.01	**Total poutres en acier laminé**	QF	4,8	m									
	23.13	Linteaux en acier												
	23.13.3	Cornières de soutien de parement en profilés d'acier												
Murs ext. façade	23.13.3a	Cornières de soutien de parement en profilés d'acier												
	23.13.3a.01	Cornières de soutien de parement en profilés d'acier	PM											
	24	**Eléments de structures en bois**												
	24.1	Eléments de structures en bois												
	24.12	Eléments de charpentes de toiture en bois												
	24.12.1	Eléments de charpente de toiture en bois												
Toitures	24.12.1a	Sablières												
		Sablières 3,5/18						2	9,9					19,8
	24.12.1a.01	**Total sablières 3,5/18**	QF	19,8	m									
	24.2	Ensembles structuraux en bois												
	24.22	Planchers en bois												
	24.22.1	Plancher en bois assemblés sur place												
Planchers intérieurs	24.22.1a	Solives revêtues d'un platelage												
		plancher combles						1	9,6	6				57,6
		déduction trappe accès grenier						-1	1,2	0,8				-0,96
	24.22.1a.01	**Total plancher en bois**	QF	56,64	m²									
	24.23	Charpentes de toiture en bois												
	24.23.2	Charpentes de toiture préfabriquées												
Toitures	24.23.2a	Fermettes de toiture préfabriquées en bois massif												
		Fermettes de toiture préfabriquées en bois massif						17						17
	24.23.2a.01	**Total fermettes**	QF	17	pc									
	26	**Etanchéisation et isolation**												
	26.1	Etanchéisation aux matières liquides												
	26.11	Feuilles et membranes d'étanchéité à l'eau												
	26.11.1	Membranes souples - Membranes												
Murs ext. façade	26.11.1a	Couches d'étanchéité - membranes / PE												
	26.11.1a.01	**Couches d'étanchéité - membranes / PE**	PM											
Fondations	26.11.1f	Couches d'étanchéité - membranes à pastilles												
		Couches d'étanchéité - membranes à pastilles façades						2	10,6	0,9				19,08
		Couches d'étanchéité - membranes à pastilles pignons						2	7	0,9				12,6
	26.11.1f.01	**Total membranes à pastilles**	QF	31,68	m²									
	26.12	Traitements d'étanchéisation												
	26.12.1	Cimentage												
Fondations	26.12.1a	Etanchéité - cimentage												
		Etanchéité - cimentage façades						2	10,6	0,52				11,02
		Etanchéité - cimentage pignons						2	7	0,52				7,28
	26.12.1a.01	**Total cimentage murs enterrés**	QF	18,30	m²									
	26.12.2	Badigeonnage												
Fondations	26.12.2a	Etanchéité - badigeonnage												
		Etanchéité - badigeonnage façades						2	10,6	0,52				11,02

METRE RECAPITULATIF								METRE DETAILLE					
Composant constructif (cfr Grille analyse)	**n° article / poste**	**Désignation**	**NM**	**Quantité**	**U**	**PU**	**Total**	**Nb**	**Long**	**Larg**	**Haut**	**Fact**	**Total**
		Etanchéité - badigeonnage pignons						2	7	0,52			7,28
	26.12.2a.01	**Total badigeonnage murs enterrés**	QF	18,30	m²								
	26.4	Isolation											
	26.41	Isolation en panneaux											
	26.41.1	Isolation en panneaux - matières synthétiques											
Murs ext. façade	26.41.1d	Isolation en panneaux - polyuréthane (PUR) - épaisseur 10 cm -											
		isolant PUR façade avant rez-de-chaussée						1	10,4	2,9			30,16
		isolant PUR façade avant étage						1	10,4	2,82			29,33
		isolant PUR façade arrière rez-de-chaussée						1	6,8	2,9			19,72
		isolant PUR façade arrière étage						1	6,8	2,82			19,18
		pignon 1 rez-de-chaussée						1	6,8	2,9			19,72
		pignon 2 rez-de-chaussée						1	6,8	2,9			19,72
		pignon 1 étage						1	6,8	2,82			19,18
		pignon 1 étage						1	6,8	2,82			19,18
		pignon 1 triangle						1					8,07
		pignon 1 triangle						1					8,07
		déduction porte d'entrée façade avant						-1	1,21	2,18			-2,64
		déduction fenêtre fixe façade avant						-1	1,01	3,95			-3,99
		déduction fenêtres rez-de-chaussée façade avant						-2	0,71	0,8			-1,14
		déduction fenêtres étage façade avant						-3	1,01	1,33			-4,03
		déduction ensemble porte-fenêtre fixe rez-de-chaussée façade arrière						-1	4,81	2,3			-11,06
		déduction ensemble fenêtre rez-de-chaussée façade arrière						-1	2,21	1,1			-2,43
		déduction double fenêtre étage façade avant						-1	2,21	1,68			-3,71
		déduction fenêtres étage façade arrière						-2	1,21	1,68			-4,07
	26.41.1d.01	**Total isolation PUR**	QF	159,24 112,28 65,32	m²								
	26.41.2	Isolation en panneaux - matières minérales											
Murs ext. façade	26.41.2a	Isolation en panneaux - laine minérale (MW) - épaisseur = 4cm											
		isolant LM mitoyen rez-de-chaussée						1	6,8	2,9			19,72
		isolant LM mitoyen étage						1	6,8	2,82			19,18
		isolant LM mitoyen triangle						1					8,01
	26.41.2a.01	**Total laine de roche mur mitoyen**	QF	46,91 93,81	m²								

		Human	Drone	Drone	Human		Drone		Human	Drone	Human	Drone	Drone	
		Material	**Material 0% increase**	**Material 30% increase**	**Work force**		**Work force**		**Equipment**	**Equipment**	**Total unit price**	**Total unit price Scenario 1**	**Total unit price Scenario 2**	**Management fees**
	Units	UP Material	UP Material	UP Material	*Exec. Time*	UP WF	*Exec. Time*	UP WF	UP Equipment	UP Equipment	**Total UP**	**Total UP**	**Total UP**	MF/day
<u>Walls</u>														
<u>Facade</u>														
Bricks	m^2	27,48 €	27,48 €	35,72 €	90min	52,50 €	4,24min	2,47 €	12,00 €	5,52 €	91,98 €	35,47 €	43,71 €	40,00 €
Expanded clay blocs - 14cm	m^2	10,67 €	10,67 €	13,87 €	52min	30,10 €	47,23s	0,46 €	2,50 €	1,03 €	43,27 €	12,16 €	15,36 €	40,00 €
<u>Interior bearing wall</u>														
Expanded clay blocs - 14cm	m^2	10,63 €	10,63 €	13,82 €	51min	29,75 €	47,23s	0,46 €	2,50 €	1,03 €	42,88 €	12,12 €	15,31 €	40,00 €
Expanded clay blocs - 19cm	m^2	16,53 €	16,53 €	21,49 €	60min	29,75 €	47,23s	0,46 €	2,50 €	1,03 €	48,78 €	18,02 €	22,98 €	40,00 €
<u>Interior partition wall</u>														
Expanded clay blocs	m^2	8,50 €	8,50 €	14,37 €	41min	23,80 €	47,23s	0,46 €	2,50 €	1,03 €	34,80 €	9,99 €	15,86 €	40,00 €
<u>Floors</u>														
hourdis	m^2	28,00 €	30,43 €	39,56 €	15min	8,75 €	5,89min	3,43 €	0,00 €	0,77 €	36,75 €	34,63 €	43,76 €	4,00 €

Annex 5 : Summary of the human and drone cost.

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