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Generative design and platformization:

Office practice and opportunities analysis for sustainable architectural design

Master's thesis in order to obtain a master degree in « Architectural Civil Engineering », by
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Abstract

Sustainability in architecture is a complex objective with multiple criteria to address and optimize. The use of generative design for sustainable architectural design, since it lets the users do performance-based design in a short amount of time, has a great potential providing solutions and giving an overall feedback on the performances of the design. While usual generative design tools still require computer science skills, and thus create a barrier to the use of generative design, a new kind of platform is emerging, targeting non-specialists. These toolsets present a great potential in addressing these issues, and this thesis assesses the potentialities of these platforms in what we call *sustainable generative design*.

By assessing the use of sustainable generative design in offices and the challenges to its establishment, we will be able to understand how the new generative design platforms can respond to the practice's needs. In order to do this, we have first assessed *sustainable generative design* through a state of the art, where the literature reviews helped us establish our hypotheses for the next parts of the thesis. Then, we have interviewed architects with either an expertise in sustainable design, or computational design. These interviews helped us assess the establishment of computational design, sustainable design and sustainable generative design in practices. We could also emphasize the barriers and drivers to the adoption of sustainable generative design. Afterwards, we explored a tool among the new generative design platforms, which we chose based on the types of analysis it offered. With this exploration, we could compare the platform to the characteristics of an ideal sustainable generative design platform mentioned during the interviews, and we also compared the characteristics of the tool to a framework chosen in literature, to assess whether this framework could be made using the tool.

The obtained results highlight the potentialities of these new generative design platforms in sustainable architecture and the opportunities they present for the AECO industry.

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1 Introduction

1.1 Context

Sustainability is a complex topic to address in architecture, with many criteria to take into account. While generative design allows its user to do performance-based design, it presents a great potential for sustainable architecture. Though, the use of generative design requires computer science skills, which are still in the early stages of the adoption in the AECO industry. But during the last few years, cloud-based generative design platforms for non-experts have been flourishing. These platforms are claiming to let the user generate buildings in just a few clicks, and to analyze the different propositions, thus providing decision support in early stage urban planning and architectural design. These new platforms have a great potential for non-expert audiences, private or public, such as real estate developers or even governments and planners. Since the environmental factors are difficult to take into account in early stage design, especially for non-experts, these platforms could have a great potential in helping taking these factors into account in the early stages of the design.

1.2 Research objectives and problem statement

This work aims to assess whether the new cloud-based generative design platforms are corresponding to a need in the industry. In order to understand the potentialities of such platforms could bring in the industry, this work will assess the following topics:

- The use of generative design for sustainable design in offices
- The challenges to the adoption of generative design for sustainable design
- If one of the new generative design platforms corresponds to a need in the industry

In order to do this, we have first assessed *sustainable generative design* through a state of the art, where the literature reviews helped us establish our hypotheses for the next parts of the thesis. Then, we have interviewed architects with either an expertise in sustainable design, or computational design. These interviews helped us assess the establishment of computational design, sustainable design and sustainable generative design in practices. We could also emphasize the barriers and drivers to the adoption of sustainable generative design. Afterwards, we explored a tool among the new generative design platforms, which we chose based on the types of analysis it offered. With this exploration, we could compare the platform to the characteristics of an ideal sustainable generative design platform mentioned during the interviews, and we also compared the characteristics of the tool to a framework chosen in literature, to assess whether this framework could be made using the tool.

2 State of the art

Since this study aims to benchmark the practices and adoption of generative design as a tool for sustainable architectural design, and then to evaluate potential opportunities in new platforms, we will first define the main concepts in computational design and what we call sustainable generative design (SGD), followed by the adoption and use of SGD in practices, then a review of the platforms used in research.

2.1 Computational design: definitions

While most people might define computational design (CD) as an approach based on the use of computer tools to develop design solutions, Terzidis (2004) defines CD as the use of algorithms to conceive designs, thus changing the whole process of the design . Computational design can be defined by Caetano, et al. (2020) as a "*design process that uses computational skills through a set of activities, such as automating design procedures, running design tasks simultaneously, managing large amounts of information, incorporating and propagating changes in a quick and flexible manner and assisting designers in form-fitting processes through automated feedback, such as mapping simulation results"* (Caetano, et al., 2020).

Computational design can be divided into three subsets: Parametric, Generative or Algorithmic. For a better understanding of the scope of this work, we will define each subset and their applications.

2.1.1 Parametric design

Since there's no clear consensus on a definition for parametric design, we will define parametric design by describing the approach.

According to Janssen & Stouffs (2015), *"A parametric model consists of a collection of modelling operations that are linked into a network that can be topologically sorted, that is, the order of execution of the modeling operations can be defined prior to execution"* . This system consists of a range of possible inputs, the parameters, fed into a set of clear rules and constraints in a specific order to solve these inputs, thus producing the outputs. The inputs will have a direct impact on the outputs, thus changing the inputs will generate different outputs, for the same parametric system (de Boissieu, 2022).

What differentiates parametric design from its other counterparts is its acyclic nature, thus constraining the data propagation in one direction (Janssen & Stouffs, 2015) (de Boissieu, 2022) .

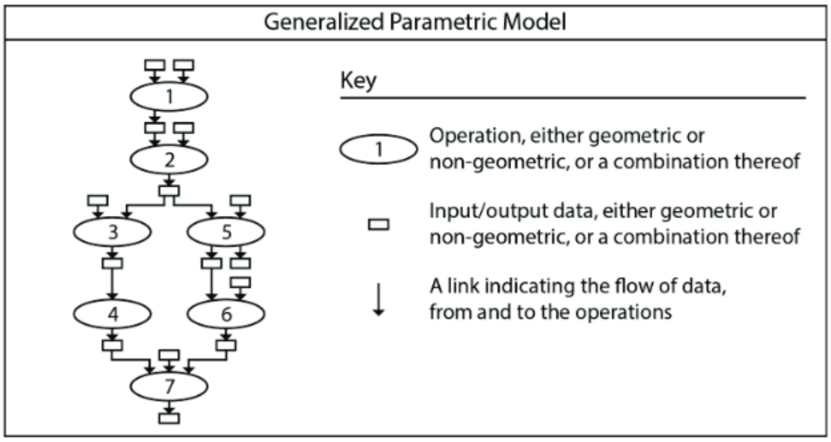

Figure 1 : Example of generalized parametric model graph, (Janssen, et al., 2015)

Parametric design requires creativity and design skills, so the designer can define the parametric system and explore meaningful results called instances (de Boissieu, 2022).

2.1.2 Generative design

Unlike parametric design, generative design is a non-linear process and its algorithms are more autonomous than in parametric design. The designer can then define problem spaces through a sorted set of instructions, and produce a range of outputs, the solution space, from a range of defined inputs. To sort the solution space, specific objectives can be targeted, allowing the generative design process to be used in optimization methods. Generative design methods have a tendency to produce unexpected results, such as the "*happy accidents*" of Chaszar and Joyce (2016).

A good example for generative design is performance-based generative design systems. The algorithms allow the user to find design solutions based on a performance target set by the designer (Caetano, et al., 2020). The advantages of generative over parametric design are the optimization process, which leads to the proposition of different solutions, sorted by the performance criteria of the solutions.

2.1.3 Algorithmic design

By definition, "*algorithmic design (AD) is a design process based on algorithms"* (Caetano, et al., 2020), thus, AD is a subset of Generative design. There is a correlation between the algorithm and the generated model, helping the designer anticipating the outcome and producing fewer surprising results. For example, Caetano et al. says "*a program that produces a model of a building by separately creating its slabs, columns, beams, walls, windows, and so on should be considered an example of AD because tracking the parts of the code that produce a given part of the model is easy"* (Caetano, et al., 2020).

A common example of algorithmic design is genetic algorithms, which are optimization algorithms based on the biological evolutionary process. Genetic algorithms are mimicking the natural evolution: to optimize an initialized set of objects, they use similar steps: evaluation and selection, recombination and mutation (Rüdenauer & Dohmen, 2007). In this case, the designer defines a set of optimization criteria as the input of a "fitness function", which will provide, sort, recombine and “mute” solutions in a cyclical and continuous manner, until either an abort criterion is reached or the system achieves an equilibrium where every new solution is less fit than the previous ones.

2.1.4 Sustainable generative design

Sustainability in architecture is a complex objective with multiple criteria to address and optimize. Since generative design allows the designers to do performance-based design in a short amount of time, it has a great potential in providing solutions for sustainable architectural design. Thus, this study will focus on what we call *sustainable generative design*, so the use of generative design applied to sustainable architectural design.

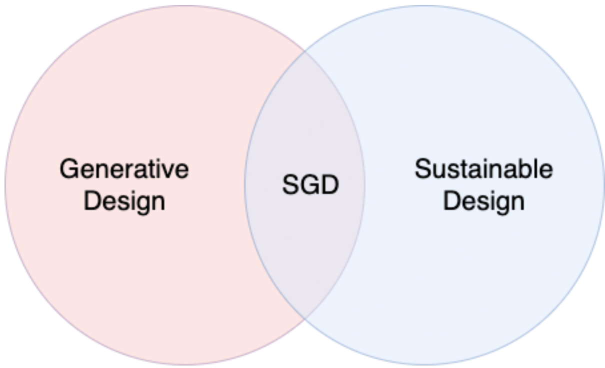

Figure 2 : Sustainable generative design

Although the AEC industry does not have the computational resources that can provide formal guidelines towards a sustainable design using a generative process (Thariyan , et al., 2017), the use of performance-driven design in architectural design workflows could allow the designer to test various design options and have an overall feedback on the design’s performance. However, the interpretation of the data and the understanding of the generative design process with its parameters and the performance criteria is crucial (Duering, et al., 2020) since the quantifying of a design’s performance is not necessarily clear on why the design performs the way it does. Thus, if the data interpretation and the approaches toward dimensionality reduction are inadequate, the designer can be confused on how to improve his design. The sustainability of architecture is difficult to quantify and need more research in order to do so. These research gaps are leading to a lack of integrated computational frameworks as well as interpretable information, which leads to an absence of synthetized information to determine the best architectural design strategy for the designers (Chang, et al., 2019) (Elshani, et al., 2021).

According to Elshani, et al. (2021) the performance of buildings can be sorted into three main categories of sustainability: Social, Environmental and Economical. To make the most from generative design, one must focus on evaluation metrics that highly depend on the urban and architectural form. Since there’s no clear consensus on the indicators to integrate, we will focus in this work on the environmental aspect, with indicators such as wind comfort and sunlight hours.

2.2 Sustainable generative design in literature

The use of programming in architecture has only been considered recently by architects, as they become aware of its potential and introduce it in their design practices, partially due to the rise of programming languages designed to be easy to learn (Caetano & Leitão, 2016). This section aims to define the different potential stakeholders of SGD in practices, whether they may be specialists in generative design or sustainable design; the roles they take in their practices and their skills in both generative design and sustainable architectural design.

2.2.1 Roles and skills

The lack of research papers on the subjects shows us that the practice of sustainable generative design is scattered, and not yet established in most architectural practices. Indeed, most practices haven't got any specified role for designers with computational design skills, thus generative design being a subset of computational design and an even more *niche* skill, we can expect the roles of "generative designers" to be similar to those attributed to "computational designers".

Even though the article addresses the practice of computational design instead of generative design practice, A. de Boissieu (2020) describes two main categories of roles that may be transposed to generative design: the "*computational designer"* and the "*computational design specialist".* The first category can be identified as Deutsch's "*superuser"*: the identification of the "*computational designer"* is more of a skillset and a state of mind than a defined role. Indeed, as Deutsch says, "*a specialist came to be this generation's generalist architect"* (Deutsch, 2019) which means that even with their specific skillsets, the "*superusers"* often still work as generalist architects, generally developing and using their skills as a personal initiative, and leading to having a lack of recognition in their practice. The other role described by A. de Boissieu, the "*computational design specialist"*, is mostly found in large architectural practices, such as *Zaha Hadid Architects,* or consultancy practices and represents architects working in a role dedicated to computational design. In this case, the transposition of the specialist role in generative design may not be relevant, since dedicated roles are still specific to some large practices, even in the wider scope of computational design, while these roles aren't established in small or medium practices, where a gap of knowledge persists although these firms represent 99% of the European architects (Stals, et al., 2021).

While no articles have been found regarding the type of users in sustainable generative design, only assumptions can be made.

Since most articles assessing sustainable generative design are based on academic research, it can be assumed that the practice will be mostly project-oriented, used to solve specific problems instead of being like consultancy practices with an expertise in sustainable generative design. As for the designers involved, since the use of generative design implies a developed skillset in it; we can expect the different users to be at least considered as experts in generative design alone. Regarding their roles in their practices and considering the lack of literature on the subject, it is very much likely that the designers working on SGD in projects do not have a dedicated role to SGD.

The scope of this work will be to map these practices and understand in which roles these "SGD designers" fit in, based on A. de Boissieu's work (2020), who has made a map of the different roles in architectural practices, using Deutsch's theory of Superusers (2019) :

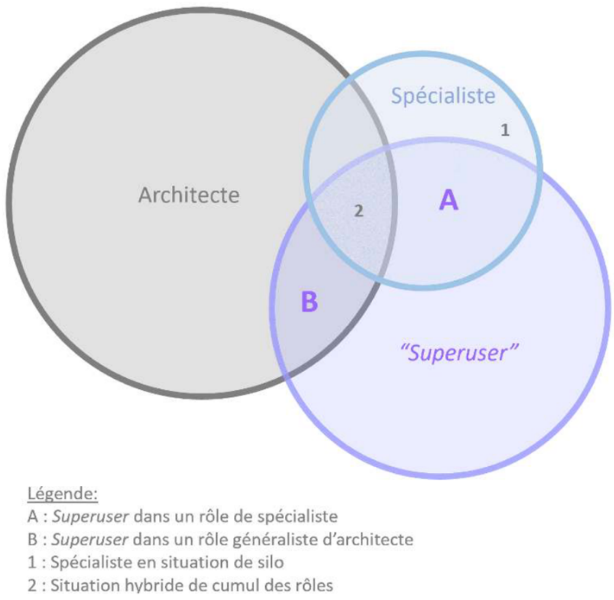

Figure 3 : Roles of *Superusers* in architectural practices (de Boissieu, 2020)

To understand the roles of the different stakeholders, we described three main potential roles: the generalist architect, the SD specialist in a dedicated role and the GD specialist in a dedicated role.

From these three roles, different combinations can happen: the overlap 1 represents designer working both as generalist on projects and as a specialist in GD. Overlap 2 represents a generalist architect combining roles as specialist in GD and SD. Like Overlap 1, Overlap 3 would be an architect working both as generalist and as SD specialist; while overlap 4 would be a SGD specialist working in a dedicated role. We can note that the "generalist architect" role has not impact on their skillsets in both generative or sustainable design. A generalist can either have developed skills in SD and GD or not at all.

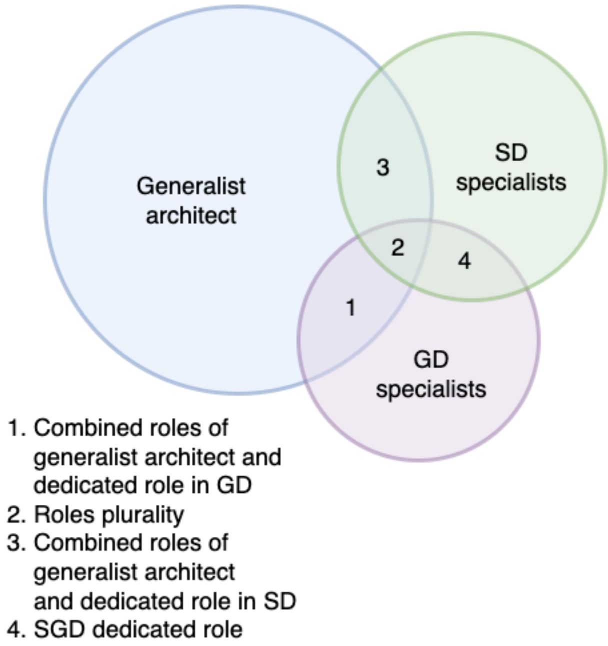

Figure 4 : Potential roles of SGD designers in practices

2.2.2 Sustainable generative design practices in literature

Although large practices and academics have done some research on the use of computational design for sustainable architectural design, the fact that computational design is not established in the AEC industry makes the use of CD for sustainable architectural design very niche and adopted only for specific use. In this section, we are going to assess how generative design is applied in sustainable architecture in the academic context.

2.2.2.1 Different types of utilization

At the urban scale, some academics like Elshani, et al. (2021) tried to define a framework to measure the sustainability and interpret the performance of urban form, with the help of generative design tools like Grasshopper. As promising the framework looked, it did not cover all issues related to sustainability and is recommended by the authors to be used as a supplement to the existing tools (Elshani, et al., 2021). Fink, et al. (2021) also created a workflow on Grasshopper for Rhino 3D, using ladybug tools, but the approach was limited to spatial, economic and climate parameters (Fink, et al., 2021). Yoffe, et al. (2020) proposed a workflow on Grasshopper to reduce the expert dependency on sustainability evaluation (Yoffe, et al., 2020). A common remark in these documents was that there's a lack of holistic approach in the application of analysis methods (Fink & Koenig, 2019) and there's no consensus on the key parameters to define in the algorithms, even 30 years after the adoption of sustainability rating systems (SRS) (Yoffe, et al., 2020). As said by Koening, et al. (2020) "most of these propositions have produced separate tools and disconnected workflows" (Koenig, et al., 2020).

Considering the architectural scale, most papers shows us that generative design is used to solve very specific problems regarding sustainability, as single-objective optimization (Koenig, et al., 2020): Pantazis, et al. (2018) developed a framework to generate and evaluate façade designs; Martinho, et al., (2019) established a workflow to evaluate the performance of adaptive façades. On the other hand, Sepúlveda, et al., (2020) created a "multi-objective optimization workflow" for the design of building envelopes in cold climates, but only based on solar analysis with two parameters.

2.2.2.2 Sustainability criteria assessed in literature

When addressing sustainability issues at the urban scale, most designers will assess issues like solar access, solar radiation (Sepúlveda & De Luca, 2020), accessibility, microclimate with solar radiation and wind flows (Duering, et al., 2020). Fink, et al., (2019) also proposes an integrated parametric design addressing geometry (e.g. building coverage ratio), accessibility, visual integration, environmental performance, solar radiation and outdoor comfort parameters. We can also note that Spacemaker (Haukeland, 2019) runs similar integrated analysis, with respectively an area analysis (e.g. gross floor area), building analysis (e.g. number and volumes of buildings, areas of the façades…), daylight analysis (obstruction angle and vertical sky component), noise, outdoor area, sun, view, wind and microclimate analysis.

Another recurring parameter is Energy. Shi, et al. (2017) have based their workflow on the urban energy simulation program City Energy Analyst, coupling it with an algorithmic optimization engine, while Allegrini, et al. (2015) have reviewed the simulation tools for district-scale energy systems, concluding that there's no "*one-size-fits-all*" simulation just like there is no single model addressing all the physical processes involved, and the designers have to choose the right simulation process on a case by case basis.

The lack of consensus on the parameters to evaluate the designs contributes to the lack of defined workflows to generate sustainable designs. To address the problem, Elshani, et al. (2021) proposed a framework to interpret the performance of the urban form, based on three sustainability pillars: social, environmental and economical. Each of these pillars have an evaluation method and an application for performance space exploration.

2.3 Sustainable generative design toolsets

An important element to take into account while assessing the establishment of SGD, is the tools. Although programming used to be considered a specialized skill (Caetano & Leitão, 2016), thus creating a barrier in the adoption of generative design, tools using visual programming have been helping lowering this barrier. With non-expert platforms emerging, we assessed the different tools used for generative design in architecture.

2.3.1 Computational design tools and their applicability to generative design

While tools like Revit or ArchiCAD may come to mind when talking about computational design, the fact that they rely mostly on predefined objects, constraining the designer to use the existing library of rules and relationships makes these tools not flexible enough to be recognized as CD tools without the use of programming (de Boissieu, 2022).

A popular type of computational design toolsets in architecture are the visual programming tools. Its graph-based representation of the parameters and the fact that textual programming skills are not required to use it makes it easier to understand and more accessible amongst the designers, though still requiring some computer science skills to understand how it works. One of the most popular visual programming tools amongst designers is Grasshopper (Rutten, 2007). Its high degree of flexibility and the possibility to use textual programming for more advanced designs makes it one of the most popular platforms, combined with its numerous plugins. While parametric design is easier to implement due to its unidirectional characteristic (de Boissieu, 2022), generative and algorithmic designs can be implemented with the help of plugins or textual programming.

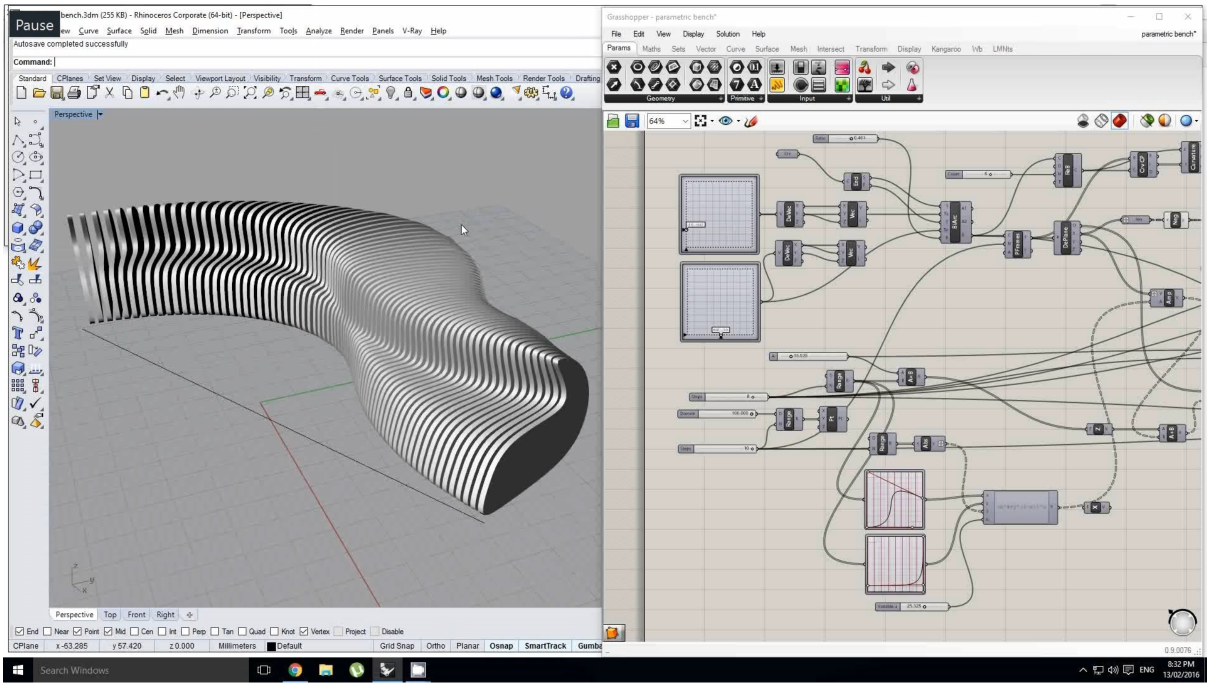

Figure 5 : Grasshopper interface (Sawantt , 2021)

2.3.2 Platformization in generative design

While visual programming tools still require computer science skills, more and more tools are improving user access to algorithms and to library management systems. To address these issues, a new kind of computational design toolset targeting non-specialists is emerging. These toolsets are cloud-based platforms like Spacemaker (Haukeland, 2019), Testfit (Harness & Griege, 2017) or Archistar (Coorey, 2018), are meant for various objectives, such as building configurators, urban feasibility generation and evaluation or automated parking layouts. These platforms are available to non-specialists, like architects or engineers but also property developers, town planners and investors.

In these platforms, the user is allowed to select a construction site and evaluate thousands design options in just a few steps. The design options are evaluated through a set of performance objectives, such as daylight, unit mix, density or even cost. Some other platforms like Hypar (Keough, 2019) allows designers to implement their algorithms, while allowing other users to access them (de Boissieu, 2022). Although easy to use, these platforms are made for early stage design and their outputs are still made for conceptual phase of the project (Cao, et al., 2021).

In order to provide their services, these new platforms require large and detailed data sets, which the AEC industry does not fully have yet (de Boissieu, 2022). Thus, one must be careful using these services, as most platforms are not transparent regarding the data and the analysis methods employed.

2.3.3 Generative design toolsets for sustainable architectural design

In this chapter, we will describe the main tools used for sustainable architectural design. Even though efficient simulation tools are on the market, they are mostly used during the detailed design stage (Martinho, et al., 2019).

2.3.3.1 Grasshopper and other visual programming tools

The most recurring software used in literature workflows are Grasshopper and Dynamo, due to their high flexibility and the large catalog of plugins making these software highly customizable to meet the needs of the designers, thus making them well-established in the computational design practice.

To some extents, a specific program is created to meet the demand, such as Algorithmic-Based Analysis made by Leitão, et al. (2017) to solve the problem that each analysis program need a specific building model exported in a particular format.

One of the most commonly used tools in computational design for sustainable architecture is Rhino/Grasshopper with its numerous plugins. To be able to use Grasshopper for generative design, a plugin like Galapagos or Octopus is required, permitting the designer to create genetic algorithms. We also observed the use of Dynamo, but on a less regular basis, and only applied to parametric design. Although the visual programming interface, combined with its high level of flexibility and its large community of developers are its main advantages, its results are crippled by a relative computational slowness, especially problematic for multi-criteria evolutionary optimization process (Duering, et al., 2020).

To extend the use of Grasshopper, and integrate climatic data, Ladybug Tools (Sadeghipour Roudsari & Mackey, 2013) provides a series of interactive 3D graphics and metrics based on several validated simulation engines, such as EnergyPlus/Openstudio. It runs within the 3D modeling software and the data transfer is seamless between deployed generative components and simulation engines. The ladybug tools are sorted into three plugins: Ladybug, Honeybee, Butterfly and Dragonfly. For instance, Ladybug provides 2D and 3D interactive climate graphics to support the decision-making process, while Honeybee creates, runs and visualizes daylight simulations, energy models and envelope heat flow. "*Butterfly is a plugin and a library to create and run advanced computational fluid dynamic simulations (CFD) while Dragonfly models large-scale climate phenomena such as heat island or climate change, and local climate factors such as topography*" (Sadeghipour Roudsari & Mackey, 2013). These plugins are made for different stages of the design and different applications. Dragonfly is more suited for urban projects, while Honeybee is building-centered. While Ladybug is mostly made for early-stage design, Honeybee runs advanced daylighting and thermodynamic modeling suited for mid and later stages of design.

2.3.3.2 At the urban scale

Although Grasshopper remains a popular choice when considering generative design at the urban scale, other platforms like CityEngine, which supports the multi-scale rule-based planning and modeling take an increasing part of the market. DecodingSpaces synthesizes spatial configurations for road networks, parcels and building volumes, allowing the designer to generate urban design and explore many possible solutions quickly. City Induction also supports urban layout generation and exploration, among others (Lee, et al., 2019).

2.3.3.3 What about the cloud-based platforms?

While platforms like Testfit (Harness & Griege, 2017), PRISM (Mayor of London, 2019) and Archistar (Coorey, 2018) are focused on feasibility studies, with an economic-centered approach of urban planning. Since these tools rely mostly on already implemented datasets and embedded generative functions, their use is limited to the existing libraries. Since Hypar (Keough, 2019) is designed as a customizable platform, it allows any user to upload his own algorithm, making its use extremely flexible. For the non-specialist, the accessibility of the uploaded algorithms and the growing community of Hypar makes it promising for sustainable architectural design. As for Spacemaker (Haukeland, 2019), it aims to help designing more sustainable cities, with embedded analysis for daylight, noise, sun hours, wind and microclimate. The accessibility and the transparency of Spacemaker on its functions makes them easy to understand and while the calculations are simplified, it remains well-suited for early stage planning. While these platforms are new to the industry, their development toward sustainability is promising.

2.3.3.4 Other user-made platforms

Since the generative design toolsets are still in development, some designers are creating their own tools to answer specific needs. The fact that only few open-source software are available in the industry doesn't help, but communities of computational designers are emerging, and are creating significant knowledge bases helping both professionals and amateurs (de Boissieu, 2022). Still the development of tools and ecosystem of tools is only addressed for specific issues, and are carried only within large architectural offices or academic research.

2.4 Discussion

We learned in this section that even with all the advantages that generative design has to offer, it is still not adopted in the day-to-day architectural practice. Contributing to this phenomenon is the lack of literature on the subject and lack of recognition to the computational design specialists, which are employed as specialists only in large architectural practices, the others having an integrated role and having much less time to develop their skills.

When used for sustainable architecture or urban design, the lack of defined workflows and consensus on parameters to define and restrains the designers, leading them to focus most of the time on the optimization of a single criterion as an alternative to multi-criteria optimization. The lack of specialized software creates also an issue, even with the high flexibility of Dynamo and Grasshopper, with all the plugins compatible, respectively the most used software in literature for sustainable generative design, some specialists have to create their own generative modeling tools to meet their needs. Nevertheless, these tools present a great potential if applied with the right methodology and data.

3 Methodology

3.1 Research questions

After having done a literature review in the state of the art, the following issues were raised:

1) How is SGD **established** in practice?
2) What are the **barriers and drivers** to SGD adoption?
3) Is a tool like Spacemaker responding to a **need** in the practice of SGD?

In order to answer these questions, as shown in the
below, this thesis started with a state of the art based mostly on literature reviews. The conclusions of the state of the art will serve as basis for the next part of the work, which will be divided in two parts: the interviews of experts sustainable and/or computational design, and a toolset exploration, where different generative design tools will be explored in order to choose one tool to assess in the further sections of the thesis. Then, the chosen tool will be compared to a computational framework found in literature, and to the results of the interviews.

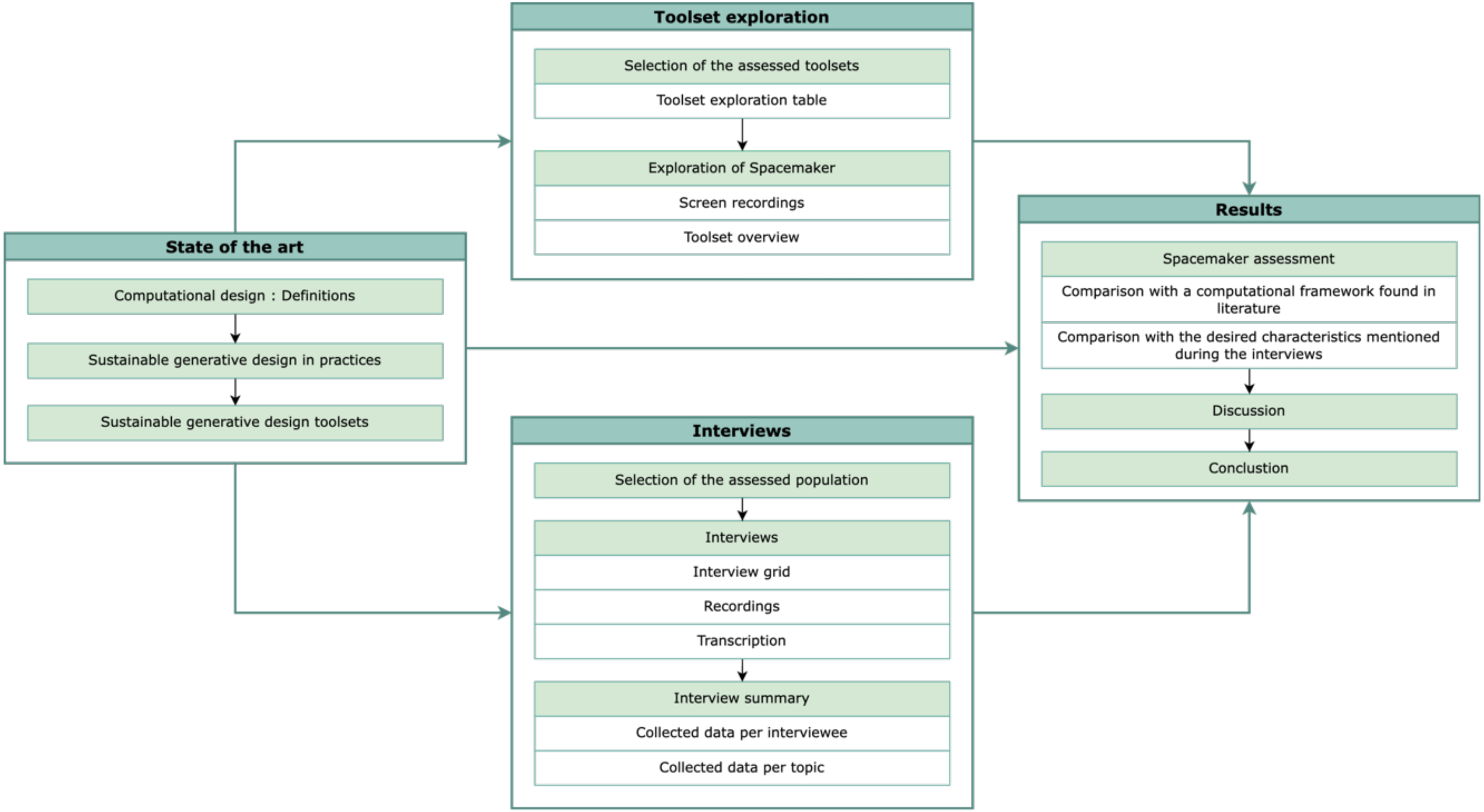

Figure 6 : General methodology of the thesis

To evaluate the establishment of SGD in practices, we have defined 6 indicators, divided in two sub-categories, as seen in the Figure 7 below. The first sub-category, the "practice" as named in the diagram, will assess how SGD is actually used. In this category, there is 5 indicators: the design stages where SGD is applied; the parts of the projects, for instance the façades; the objectives, such as solar analysis as seen in the state of the art, and the toolsets used. Regarding the other sub-category, concerning the stakeholders of SGD, we decided to assess only the roles, which can be either dedicated to SGD or integrated in a wider role, such as sustainable design specialist.

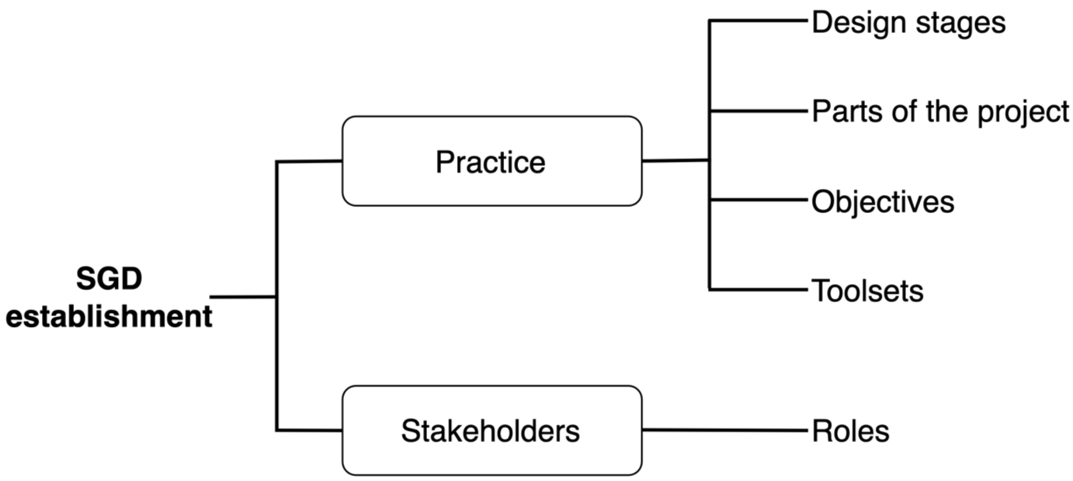

Figure 7 : Indicators to evaluate SGD establishment

3.2 Main hypothesis

When doing research about the establishment of SGD in literature, we found only sparse answers. As a hypothesis for this work, we will assume that SGD is at the most used punctually in projects, and used by architects integrated in a wider role than just an expertise in SGD. We can expect that the different stakeholders can be either experts in sustainable or computational design, or generalist architects.

To make sure we didn't miss potential objectives of SGD, we decided to keep the "sustainable design" definition instead of assessing precise sustainability criteria.

The adoption of SGD in practices has been summarized through 6 different characteristics: during which design stage it is employed, the parts of the project it targets, for which sustainability objectives it is used, if there's an optimization process, which toolset is used and what are the roles of the different stakeholders.

3.3 Assessing the roles and skills associated to SGD in practices: interview methodology

To evaluate the establishment of SGD and the roles and skills associated to SGD in practices, we decided to conduct interviews to computational design experts and sustainable design experts since no experts were found in the very *niche* SGD domain. The general approach of this problem will be to evaluate first how sustainable design and computational design can be established in practices, then evaluate the establishment of sustainable generative design.

3.3.1 Population studied

Since we approach the topic on both sides, respectively sustainable design and computational design, the experts interviewed will be from both domain of expertise. SGD experts weren't found but it doesn't mean that SGD is not used in practices. The experience of the sustainable and computational experts will help understand how SGD is established, its opportunities, and the barriers and drivers to its establishment.

Since there's a gap of knowledge regarding computational design between small and medium offices and large practices, this study will be focused on large practices. With that in mind, we have selected four practices: BSolutions, A2M and Grimshaw and their main office is respectively based in Gembloux, Bruxelles, and London.

3.3.1.1 BSolutions

BSolutions is an engineering and architecture office, with 85 collaborators and located in Gembloux, Belgium. It has been selected for its interdisciplinary feature, and its unit dedicated to sustainable development (BSolutions, 2022). In this office, we have interviewed a PhD student Charlotte Dautremont, doing her thesis both at the University of Liège and at BSolutions, where she studies collaborative practices in the integration of a systemic sustainable approach in architectural design. Her expertise in BIM practices and sustainable design makes her point of view on SGD more sustainability-oriented.

3.3.1.2 A2M

A2M is a Belgian architecture practice, with an office in Bruxelles and in New York. We've chosen this practice for its sustainable design and parametric design expertise, and we have interviewed Antoine Maes, a computational design specialist. His expertise in parametric design makes his point of view more computational design-oriented.

3.3.1.3 Grimshaw

Grimshaw is a worldwide practice awarded with more than 200 international design awards. It has been selected for this thesis because of its computational design practice expertise, and we have interviewed Andy Watts, the Director of Computational design.

3.3.2 Hypothesis

To categorize the different SGD stakeholders, though many characteristics can intervene in their identification, we decided to focus only on their roles in their office, separating them in three main categories according to the diagram Figure 4 in the state of the art: the sustainable design specialist, the generative design specialist and the computational design specialist.

3.3.3 Type and realization of the interviews

To understand how SGD is established in practices, we chose to conduct semi-directive interviews to get qualitative results answering the research questions.

Semi-directive interviews are characterized by the fact that they are not fully open like non directive interviews and not structured by a great number of questions like questionnaire surveys. The survey is structured by a guideline of open questions which need to be answered. The interviewer will not necessarily ask them all in a defined order nor defined formulation. The interviewee will be free to talk and use its own formulation and the researcher will simply center the interview on the topics targeted, if the interviewee is deviating of the subject, in the most natural way possible (Van Campenhoudt, et al., 2017). The conversation-like interview will help us get information about some subjects we didn't think about writing the interviews, making more material to assess for the final part of this work.

This interview grid has been reviewed and approved by both computational and sustainable design experts, Professor Aurélie de Boissieu and Professor Sigrid Reiter, and an interview test has been conducted to check the understandability of the questions with a PhD student already mentioned, Charlotte Dautremont.

The interview will start with an introduction on the subjects and some clarifications about the definitions of what we call sustainable design, since this subject is broad and the interviewee may be disturbed by the different definitions of sustainability that can be used. After the introduction, the interviewees are invited to introduce themselves and their role in their office.

Then, the interviews are conducted through a thematic guideline based on the different research questions and organized in three different parts: first, the sustainable design adoption in the practice, then the computational design adoption and finally the sustainable generative design adoption. The subjects are addressed in decreasing order of establishment: Sustainability is well established in the industry, while computational design is less common, and sustainable generative design very *niche*. This order will help the interviewee understand the specific subject of SGD and feel more at ease with better-known subjects. To make sure that the interviews are answering the first research question regarding the establishment of SGD in practices, each subject, such as the adoption of sustainable design, is assessed through the same indicators, such as shown in Figure 7.

Sustainable design adoption

This first part of the interview will focus on the establishment of sustainable design through an open question:
"How do you use sustainable design in the studio and in projects?"

The interviewee is free to tell us what comes to his mind when asked this question, but we will make sure that he answers six criteria through this question:

- The **design stages** during which sustainable design is applied

- The **parts of the project** where it is applied; if it concerns the whole project or only parts
- The **main objectives** addressed by the designers
- Which **certification** is applied
- Which **tools** are used
- If **optimization** process are used

Then the interviewee will be asked about the roles of the sustainable design stakeholders in the office and how they usually intervene on a project:
"Can you describe who usually intervene on sustainable design in your office? And what are their missions and how do they intervene on a project usually?"
Which will help us understand whether the stakeholders have a dedicated role or integrated in a generalist architect role.

Computational design adoption

As for sustainable design, computational design is addressed in a similar way through four criteria. The fact that we ask about computational design is to avoid disrupting the interviewee with the different definitions of parametric and generative design. After the interview, we will assess whether the interviewee is talking about computational, parametric or generative design. The question is almost the same than for sustainable design:

"*How do you use computational design in the studio and in projects?"*

Here, the criteria assessed are respectively:
- The **design stages** during which computational is used
- On which **parts of the project** is it used
- The main **objectives** addressed by the designers
- Which **toolsets** are used

To insist more on the optimization process, and assess whether the interviewee is talking about generative design or not, this topic will be addressed in a specific question:
"*Are you using computational design for simulation, evaluation or optimization? Can you give few examples?"*

"Are you using generative design? How and how often? Why?"

Then, as for sustainable design, a similar question is asked for the roles of the computational design stakeholders, helping us assess whether the roles are integrated in a generalist architect role or dedicated:
"*Can you describe who usually intervene on computational design in your office? and what are their missions and how do they intervene on a project usually?"*

Sustainable generative design adoption

To address this topic, some questions on the experience of SGD of the interviewee are asked in an indirect way, using the topics addressed just before:
"Have you ever used computational design or generative design to optimize sustainability in a project?"

Here, the interviews will be adapted whether the interviewee answers in a positive or negative way.
If the answer is negative, the next questions will be skipped until the questions on SGD perception in the section below.
If the answer is positive, the interview will be similar than with the two previous topics, beginning with another more personal question to initiate the subject:
"What role did you have when you've done sustainable generative design? Did you work only on sustainable generative design or was it integrated in a common architect role?"

"How do you use sustainable generative design in the studio/ in projects?"
Which will be assessed the same way than computational design, with the following criteria:

- The **design stages** during which SGD is used
- On which **parts of the project** is it used
- The main **objectives** by the designers
- Which **toolsets** are used
- If there's an **optimization** process or if it is used for simulation purposes

As for the other subjects,
"Can you describe the roles of the different sustainable generative design stakeholders in your office and how do they intervene on a project usually?"

Then some questions on the opinions of the interviewee will be asked:
"Are you satisfied with the way sustainable generative design is used in projects? Like the design stage when it's used? Its applications on projects? The sustainability criteria assessed?"

SGD perception

These questions are about the barriers and drivers to SGD, and can be asked in every case.
"Have you identified barriers and drivers to the adoption of sustainable generative design in your office?"
"What opportunities would sustainable generative design offer according to you?"
It will help us understand why SGD is adopted or not in practices, and what can be improved.

Ideal toolset for SGD

"How would you imagine the ideal sustainable generative design toolset?"

In the diagram below in Figure 8, we can see an overview of the interview organization:

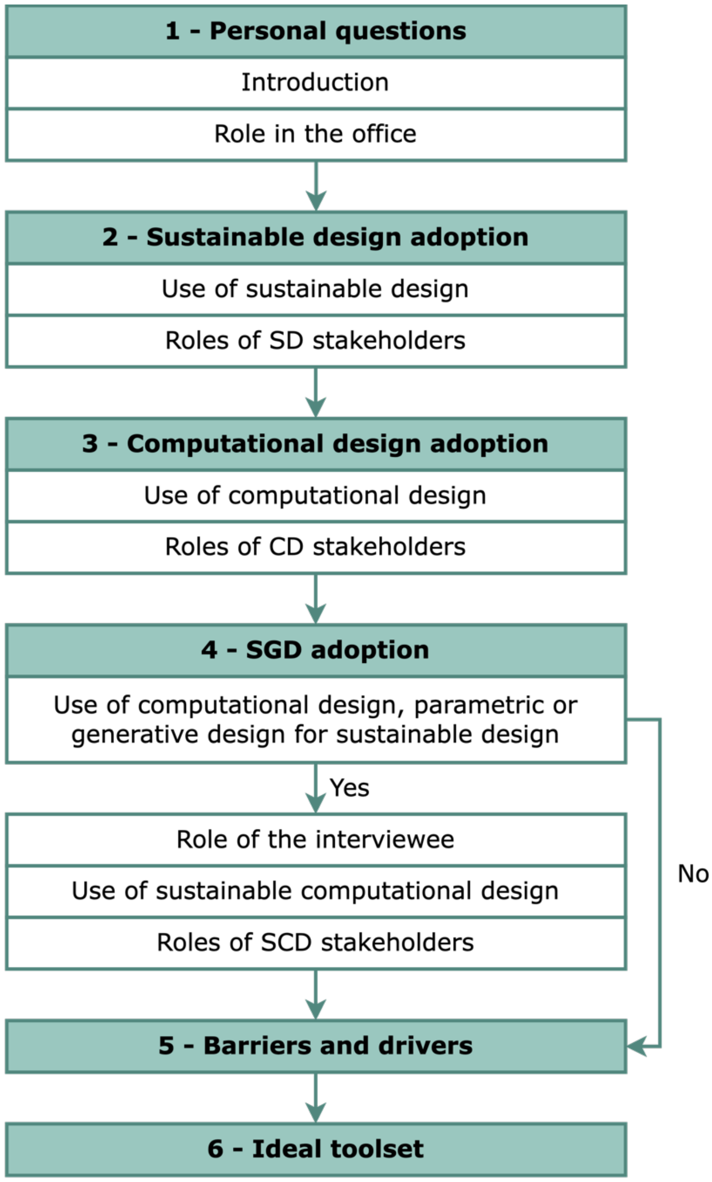

Figure 8 : Interview diagram

3.3.4 Presentation of the results

Each interview will then be transcribed and summarized two times: the first one per interviewee, then per topic, with tables to summarize each topic (sustainable design adoption; computational design adoption; SGD adoption; SGD perception and the ideal toolset for SGD)

Collected data per interviewee

For each subject covered, a summary table has been made a summary table that covers the topics discussed in the interview. For instance, the summary table for sustainable design will be as shown below, with the roles sorted in two categories: Dedicated roles, and integrated roles.

Sustainable design adoption: Office #1

Design stages	…
Parts of the project	…
Main objectives	…
Certifications	…
Toolsets	…
Optimization	…
Roles	**Dedicated** … **Integrated** …

Summary per topic

Likewise collected data per interviewee, each topic is summarized with a table.

Sustainable design adoption

	Office #1	Office #2	Office #3
Design stages	Design stage #1 …	Design stage #2 …	Design stage #3 …
Parts of the project	Parts of the project #1 …	Parts of the project #2 …	Parts of the project #3 …
Main objectives	Objectives #1 …	Objectives #2 …	Objectives #3 …
Certifications	Certifications #1 …	Certifications #2 …	Certifications #3 …
Toolsets	Tools #1 …	Tools #2 …	Tools #3 …
Optimization	Optimization #1 …	Optimization #2 …	Optimization #3 …
Roles	**Dedicated** Dedicated role #1 … **Integrated** Integrated role #1 ...	**Dedicated** Dedicated role #2 … **Integrated** Integrated role #2 ...	**Dedicated** Dedicated role #3 … **Integrated** Integrated role #3 ...

3.4 Toolsets exploration

In the state of the art, we observed that the practice of sustainable generative design depends highly on the tools used, either through its usability or the analysis it offers. Some emerging tools are claiming to help generate buildings in a few clicks, and analyzing them to help the designer choose between hundreds of options.

The toolsets exploration will help us get an overview of these emerging generative design platforms, alongside Grasshopper and the Ladybug tools, much more established in the industry. In order to do that, a table has been made using the information found on the websites of the tools, since no literature was found on these platforms. Even though the information is biased, since provided by the developers and not cross-referenced, the table will help us choose a platform to test in the next part of the thesis.

The tools will be assessed on different criteria, based on what each tool has to offer. At first, the applications of the tools will be assessed, such as the scale at which it can be used, whether it's at an urban scale or a building scale; then for the design stages, sorted into three categories: early, mid and later design stages, regarding the level of detail supported by each tool; then if the tool is meant for creating geometries such as buildings and districts.

Then we will assess the analyses offered by each tool, based on the analyses provided by each tool. Here, each analysis type can be ticked with crosses in a range from 1 to 3, according to the number of analyses provided in each type. One cross means that the analyses are in the number of 1 to 2; two crosses means 3 to 5 analyses and 3 crosses means 6 analyses or more. Based on the number of analyses provided by each tool; a score is given to compare the tools. The type of analysis provided is then assessed, whether the analysis is fast or advanced, based on the precision provided. Finally, the last criteria assessed are about the user experience of each tool, since we're assessing platforms meant to be easy to use.

To have a better overlook of the different toolsets, the table below shows these tools with their applications and the analysis they offer. Since the making of such a table could be an entire subject of a master's thesis and is not the purpose of this work, we decided to address each software through what is claimed on its website. Indeed, each criterion comes from what is claimed by at least one of the toolset developers. Thus, the information on this table is biased and is only used to have a better understanding of the current tool offer on the market.

Applications	Software	Grasshopper + Galapagos/Octopus: Ladybug	Grasshopper + Galapagos/Octopus: Honeybee	Grasshopper + Galapagos/Octopus: Butterfly	Grasshopper + Galapagos/Octopus: Dragonfly	Testfit	Hypar**	Spacemaker	PRISM	Archistar
Scale	Building	x	x	x	0	x	x	x	x	x
	Urban	x	0	/	x	x	/	x	x	x
Design stage	Early	x	0	0	x	x	x	x	x	x
	Mid	/	x	/	/	/	x	/	/	
	Later	0	x	x	/	0	0	0	0	0
Creation	Districts	0	0	0	x	x	/	x	x	x
	Buildings	0	0	0	x	x	x	x	x	x
Analysis	Area	0	0	0	0	x	/	xx	x	x
	Cost	0	0	0	0	x	/	0	0	x
	Building type	0	0	0	0	x	x	xxx	xxx	x
	Building height	0	0	0	0	x	x	x	x	x
	Topography	0	0	0	0	x	/	x	0	0
	Daylight	x	x	0	0	0	x	x	0	0
	Noise	0	0	0	0	0	/	x	0	0
	Shadow	xx	0	0	0	0	x	x	0	x
	Sun	xxx	x	0	0	0	x	x	0	x
	View	x	x	0	0	0	x	x	0	0
	Wind	0	0	x	0	0	/	x	0	x
	Energy use	0	xx	0	xxx	0	/	0	0	0
	Climate	x	0	0	x	0	/	0	0	0
	HVAC	0	x	x	0	0	/	0	0	0
	Energy potential of the site	x	0	0	x	0	/	0	0	0
	Comfort	xx	x	x	0	0	/	x	0	0
Score		11	7	3	5	5	6	14	5	7
Analysis type	Advanced	/	x	x	/	0	0	0	0	0
	Fast	x	0	0	x	x	x	x	x	x
Community-supported		x	x	x	x	0	x	/	/	/
Flexibility*		x	x	x	x	/	x	0	/	x
Accessible to non-specialists		0	0	0	0	x	x	x	x	x

x = 1 – 2; xx = 3 – 5; xxx = 6+ analyses
*Flexibility: The ability of the user to make his own analysis through visual programming, or writing code in python
** Hypar's function library is made by its community. There's no exhaustive list of the existing functions on their website.

Table 1 : Toolsets table - Exploration of the generative design platforms compared to Grasshopper alongside Ladybug tools

The different criteria assessed in this table are divided in 8 criteria:
First, the scale criterion represents whether the tool is suited for the urban scale or the architectural scale, or both. Then, the design stage criterion assesses the design stage where the tool is most suited to be used. The "creation" criterion represents the fact that the tool is made to design buildings or districts, or just analyze an existing project.

On the "analysis" side, it assesses the different types of analysis that can be done using the tool. Since the table is made relying only on the websites of the different tools, we didn't have an exhaustive list of each analysis done by the program on every website making it more difficult to assess the total number of analysis proposed by the tools, especially for the non-specialist tools. We tried to show the gap of information by ticking the boxes of the analysis done instead of counting them by criteria. To have an idea of the number of analyses provided by the tools, we scaled the analysis in a range from 1 cross to 3. One cross means that the analysis number is in a range of 1 to 2 analyses; two crosses means that the number of analyses is in a range from 3 to 5 and three crosses means that there's six analyses or more. Based on the number of crosses in the "analysis" part, a score has been provided to each program.

Then, the analysis type is to have an idea of the reliability of the analysis performed: the "advanced analysis" criterion helps us understand whether the analysis is precise or not, then the "fast" criterion helps us assess the time consumed in the analysis.

The last three criteria are more based on the user experience of each tool: first, the community criterion is based on the fact that the community can actively participate in the evolution of the tool. For instance, Hypar highly relies on its community to create the different analysis proposed by the tool. This first criterion is linked to the second one, "flexibility", which assess whether the creation of an analysis is easily accessible to any random user, or not. Then, the third criterion assesses whether the tool is accessible to non-specialists or not, where "non-specialists" can mean either computational design specialists or sustainable design specialists.

Although its use is limited by some biases, like the fact that the analysis criteria does not assess the reliability of the analysis done, which can vary a lot between the different tools; the table made in this section helps us getting an overview of the different generative design tools dans what they can offer.

3.4.1 Spacemaker exploration methodology

This section consists in testing a chosen tool to understand how it works, by drawing a project in the platform and analyzing it. The goal is to assess if it performs the analysis claimed and if the tool is easy to use, and what are the advantages and disadvantages of such a tool.
Using the table done in the toolset exploration, we have chosen the platform to assess with the highest score, which is Spacemaker.

According to its developers, Spacemaker is a cloud-based AI software made for collaborating, analyzing and designing real estate sites (Haukeland, 2019) and targets architects as well as real estate developers. This platform is meant to be easy to use and accessible, and help designing projects faster by generating hundreds of building options and analyzing them. In a few clicks, one can design buildings on a chosen site, though with limited features and a simple geometry, and analyze their characteristics.

Since the University couldn't afford a license for this software, this work was based only on a two-week trial license. The project couldn't be exported but a "view only" access was still possible even after the end of the trial. These conditions have had a great impact on the methodology of this part of the work, and on the criteria assessed. Nevertheless, in this short amount of time, we could have a complete overview of the platform.

3.4.2 Hypothesis

As hypothesis for this part of the thesis, we expect that the analyses provided by Spacemaker may be unreliable and considered with caution. Spacemaker may also not meet the desired characteristics mentioned during the interviews, as experts are interviewed and the tool targets non-experts.

3.4.3 Case study

To understand how the tool is working, we decided to work on a site located in Sart-Tilman, based on the *Ingénierie des Ambiances Urbaines* course in the second master in architectural engineering, lectured by professor Sigrid Reiter. The first reason for the use of this assignment was to try to create a sustainable project using the platform and comparing the solutions provided by the platform to the projects designed by the students of the course. This proposal was rejected since we couldn't afford a license for the tool, but we kept the assignment as a basis for the exploration of the tool. Furthermore, the fact that Spacemaker targets early stage planning makes the use of other tools necessary for the next stages of the design.

The site is located in Sart-Tilman, between an ecodistrict, student homes and the campus of the University of Liège. It is bordered by a wood, and partially covered by it, which is one of the biggest assets of the site. During the exploration, we tried to see how we could take these elements into account in the platform and how it would influence the different designs generated.

We began the process with the drawing of the site limits. It was drawn approximately in the platform, because it didn't fit the proposed site limits, but it could have been imported with a DXF file or a Shapefile if we had the corresponding files. The lack of precision offered by the program, even if it was intuitive and well documented to understand how to use it, is one of the main flaws encountered during this part of the exercise. The obtained site can be seen in red in Figure 11.

Figure 9 : Site in the *Ingénierie des Ambiances Urbaines* assignment

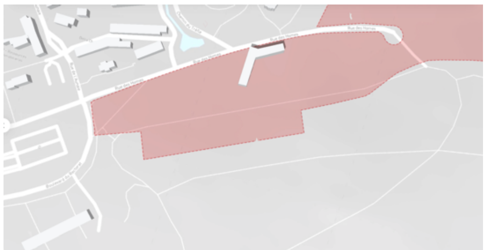

Figure 10 : Site proposed in Spacemaker

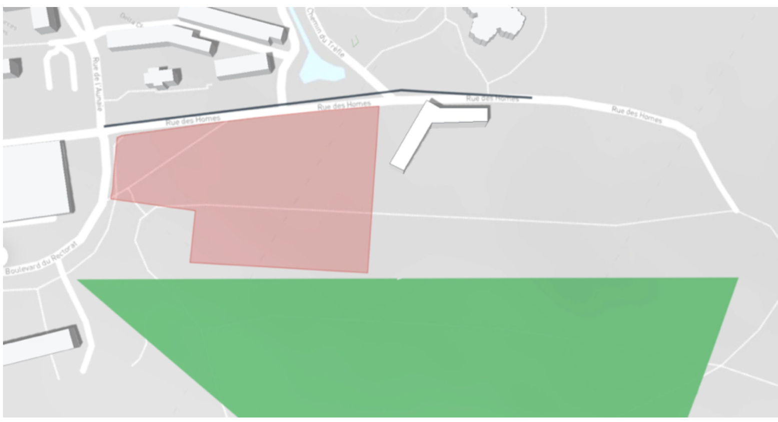

Figure 11 : Final site used during the toolset exploration

During the setup of the project, more information where added to the site: views of interest, represented by the geometry in solid green color in Figure 11, and vegetation in and surrounding the site. Other information, such as roads and some surrounding buildings height were corrected to be integrated in the analysis, even though the correction was made in an approximate way. Indeed, the main goal of the exploration wasn't to analyze precisely building options and their interaction with the surroundings, but rather see and understand what the platform proposes and how it can be done.

Figure 12 : Site setup with vegetation and surrounding buildings

3.4.4 Data collected

Once the site was set up, the exploration of the analysis proposed by the platform began. The exploration of the different options has been made in a rather intuitive manner, and based following the tutorials provided by the platform. The goal here was to assess if the platform was easy to use, and which analysis could be performed. The data was collected with the help of screen recordings, as well as technical documentation on the website for further information, such as understanding how an analysis is calculated, or where does the data comes from. The toolsets table will be then corrected according to the information collected during the exploration of Spacemaker.

3.4.5 Toolset exploration methodology summary

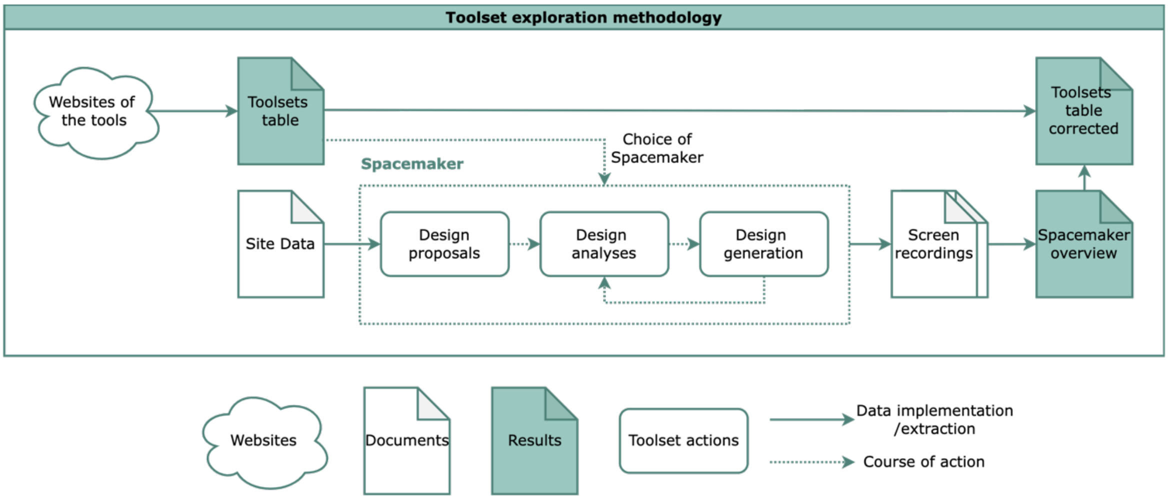

Figure 13 : Toolset exploration methodology diagram

3.4.6 Comparison of Spacemaker with a computational framework found in literature

To assess whether Spacemaker could be used in practice, we've decided to compare it first to a computational framework found in literature, which is in the article *"Measuring sustainability and urban data operationalization: An integrated computational framework to evaluate and interpret the performance of the urban form"* by Elshani, et al. (2021). This particular framework has been chosen because it focuses on sustainability metrics that highly depend on the urban form. Furthermore, both Spacemaker and the computational framework are focusing on urban form generation, though having a low level of detail, and are meant to identify and fix problematic issues during early stage planning.

Since the article doesn't give much detail in the way the criteria are assessed, we have focused on the type of analyses, and have assessed Spacemaker by comparing the type of analyses it performs to the analyses made in the framework.

3.4.7 Comparison Spacemaker with the results of the interviews

Once the interviews analyzed, we've compared Spacemaker to the results of the last question, concerning the ideal tools according to the interviewees. First, the ideal toolset characteristics will be sorted according to the number of interviewees that have mentioned them. It will help us give a weight to the characteristics and separate them according to their importance.

4 Results

4.1 Interviews

In order to understand how SGD is established in offices, interviews were conducted with architects with either an expertise in sustainable design or computational design.

4.1.1 Collected data per interviewees

1. Charlotte DAUTREMONT – Bsolutions

Charlotte Dautremont is an architect and a PhD student. After her master's degree in LOCI, she worked as an architect during a few years. She's obtained two certifications, the first one at the University of Liège on BIM practices, to become BIM coordinator and the second one to become an eco-advisor. She realizes her PhD both at University of Liège and in an architecture and engineering office, BSolutions, where she studies collaborative practices in the integration of a systemic sustainable approach in architectural design.

Charlotte Dautremont – Uliege & BSolutions	
Formation	- Master's degree in architecture - PhD student - BIM coordinator certification - Eco-advisor certification
Roles	- Research
Skills	- Collaboration - Sustainable design - BIM

Table 2 : Profile of the interviewee: Charlotte Dautremont

Sustainable design adoption at BSolutions (questions 3-4)

Sustainable design is established within BSolutions mostly through **energy studies**. On one hand, with **PEB**, where the building material's energy performance can reach the legal levels as well as passive certifications, and on the other hand, through thermodynamics studies since the office is multidisciplinary with a HVAC team, with the accent on the inhabitant's comfort[1].

[1] « *[…] c'est un bureau multidisciplinaire il y a tout ce qui est technique spéciale, où par défaut sur tout projet est réalisée une étude thermodynamique donc là on est plus dans les fluides on est plus dans le confort des futurs occupants.* »
« […] on est quand même souvent dans la thématique énergétique, soit sur la performance, soit sur le système. »

The sustainable team is divided in two main parts:
The first one, composed of two engineers in architecture with a specialization in energy, which make the thermodynamics studies, while the second part of the sustainability team is composed of two architects encoding PEB. The main tools used are the PEB software, but if the building is passive it will be PMPP. For thermodynamic studies, Design Builder is used.

Since Ch. Dautremont has been organizing workshops in the office, the engineers from the sustainable team work in a collaborative way with the rest of the office[2], so that sustainability can be taken into account in earlier stages of the design, and an optimization of the design can be made according to the results obtained from the sustainability studies.[3]

They are also integrating the environmental impact of the project with the use of Totem, through Revit and Dynamo. As she says: *«The project as it is on the environmental level, does it impact [the environment] little, or not, or much and so we are in the optimization of the design process, not in the optimization of the architecture project »*[4]

According to her, the use of the LCA tool Totem optimizes the design process, not the project. So in the application of sustainable design in the office, there's actually both optimization of the project through workshops and optimization of the design process through Totem with Revit and Dynamo.

Sustainable design adoption : BSolutions

Design stages	Detailed design
Parts of the project	Materials HVAC
Main objectives	Energy performance Energy systems Comfort LCA
Certifications	PEB

[2] *« […] depuis un an et un an et demi on ressent que vraiment les ingénieurs apportent une réflexion sur la conception architecturale. »*
[3] *« Donc voilà, […] c'est plus pour optimiser le projet, mais ça n'est pas demandé ni par les fonctions publiques, ni par le client. C'est vraiment une démarche personnelle on va dire du bureau. »*
[4] « *Le projet tel qu'il est-ce qu'au niveau environnemental est-ce qu'il impacte peu, ou pas, ou beaucoup et donc là on est dans l'optimisation du processus de conception pas dans l'optimisation du projet d'architecture.* »

Toolsets	PEB PMPP Design Builder Totem
Optimization	Optimization of the project Optimization of the process
Roles	**Dedicated** Architectural engineers Architects

Table 3 : Sustainable design adoption - BSolutions

Computational design adoption at BSolutions (questions 5-6-7)

Computational design is used during later stages of the design, during execution phases, using Revit and Dynamo for data implementation and extraction. As Ch. Dautremont states: *« […] we are more about data per se than formal. We are not in geometry. »*[5]

Computational design is used for the optimization of the design process, using collaboration through BIM. There's no optimization of the geometry, since the engineers in charge of computation are focused on data extraction and implementation. It is undertaken by the BIM team, which is composed of two BIM coordinators and one BIM manager. They manage Revit alongside Dynamo. As she states: *« […] we are more about collaboration. The're [the BIM engineers] not the ones who are going to say « the building should be like this or like that » that's not their role at all. It's really about the process »*[6] So they're more about computational BIM than computational design itself, since they're more about data than design.

At BSolutions, they don't use generative design. As Ch. Dautremont says, they're limited by the tools, like PEB for instance where they have to encode the entire project and the process is difficult to reiterate because of the time and the level of detail needed to use the tools.

« Because Totem doesn't allow much in fact, so the tools that are currently available are very limiting in development. So we are limited in fact, either by the tools themselves, or by their interoperability. So in PEB, we have to encode the entire project and therefore we are limited by the data that we can reintegrate. »[7]

[5] *« […] on est plus sur de la donnée à proprement dit que du formel. On n'est pas dans la géométrie. »*

[6] *« […] on est plus sur de la collaboration. Ce n'est pas eux qui vont dire « Ah effectivement le bâtiment devrait être comme ça ou comme ça » c'est pas du tout leur rôle. C'est vraiment sur le processus. »*

[7] *« Parce que Totem ne permet pas beaucoup de choses en fait, donc les outils qui sont disponibles actuellement sont très limitatifs dans le dans le développement. Donc on est limité en fait, soit par les outils eux-mêmes, soit par leur interopérabilité. Donc la PEB, il faut encoder l'entièreté du projet et donc on est limité par les données qu'on peut réintégrer. »*

Computational design adoption : BSolutions

Computational design type	Parametric BIM
Design stages	Detailed design Tender
Parts of the project	Whole project
Main objectives	Data implementation Data recuperation LCA
Toolsets	Revit Dynamo Totem
Optimization	Optimization of the design process
Roles	**Dedicated** BIM Coordinator BIM Manager

Table 4 : Computational design adoption: BSolutions

Computational design for sustainability adoption at BSolutions (questions 9 – 12)

Since Ch. Dautremont has been putting in place collaborative workshops, there's been a shift in the design process, with a more recurring use of toolsets like Totem, linked to Revit through Dynamo, to optimize the sustainable design process and evaluate the environmental impact of the project. She insisted on the difference between the optimization of the process, and the optimization of the design:
« […] so here we are in the optimization of the design process, not in the optimization of the architecture project. These two things complement each other but are not the same. »[8]

It is used during spatial coordination and technical design phases, because of the level of detail required by Totem to compute the environmental impact of the project. Here, the computational design process can be categorized in parametric design, since there's no iteration in the process, due to the level of detail needed to use Totem and the later design stages where it can be used[9].

[8] *« […] et donc là on est dans l'optimisation du processus de conception, pas dans l'optimisation du projet d'architecture. C'est deux choses qui se complètent mais qui ne sont pas les mêmes. »*

[9] *« Il faudrait que ça arrive plus tôt, mais Totem demande un tel niveau de détails, un tel niveau de connaissance des parois qu'on est obligé d'intervenir relativement tardivement. »*

At BSolutions, despite dedicated roles for SD and CD, there's no dedicated team to the use of computational design for sustainable design. The engineers from the BIM team intervene by putting routines in place, for the import-export of data. But the decisions made using this data can be made by different profiles, according to their domain of expertise. Thus, to make a choice regarding the architecture of the project, the decision is up to the architect. If they want to optimize the structure, the final decision is up to the structural engineer[10].

Computational design for sustainability adoption: BSolutions

Computational design type	Parametric
Design stages	Detailed design Spacial coordination Technical design Tender
Parts of the project	Whole project
Main objectives	Data implementation Data recuperation LCA
Toolsets	Revit Totem Dynamo
Optimization	Optimization of the design process
Roles	**Integrated roles** BIM Coordinator BIM Manager Generalist Architects Sustainability engineers

Table 5 : Computational design for sustainability adoption: BSolutions

Sustainable generative design perception for Charlotte Dautremont (questions 13 – 15)

Things are being put in place, like the integration of sustainable skills in more integrated roles. What she wants to establish is that sustainable knowledge is found in all profiles, not just in sustainable design specialists, so that sustainability is established during various steps, in various ways on various topics. Her idea is to add a sustainability skillset to each person's professional skills, so that they can understand the results and *"that they go and find the resource persons"* to make a design more sustainable. She states: *« And so, on a project, we*

[10] *« Mais le choix reviendra toujours à l'architecte et/ou à l'ingénieur en stabilité. Si on peut faire de l'optimisation de structure ou si on veut faire des choix, le meilleur choix en tout cas au niveau architectural ça reviendra à l'architecte. Donc l'idée, c'est que l'architecte puisse faire ce choix-là et/ou l'ingénieur durable. Donc ça dépend les profils peuvent intervenir de façon différente sur les projets. »*

could have a sustainable architect ambassador or a sustainable stability engineer ambassador, and so it depends on the person, it's a bit of layers that are added. But yes, the goal would really be to integrate that at the beginning of the design, which will really make it possible to be sensitive to the issue. »[11]

The skills in sustainability are really important to Ch. Dautremont. *« […] because Totem is also something you must know how to read, understand and come up with different things so sometimes here if there was a given moment of computational design, to make façades according to the study of the environment, you have to be able to read the quantities that are given. You don't have to say, "Okay, it's red, so here I put a cap where it's blue and it's OK." Well, there's still something, there's a particle size of knowledge to have. »*[12] One must not blindly follow the tools, there must be an understanding of the results and of the solutions to provide.

According to Ch. Dautremont, no toolset can substitute the skills of someone. One must be careful to the purposes of such a tool. It can be interesting at the early stages of the design, to highlight different elements, but its use is limited by the fact that the user needs to know how the tool works in order to understand the results provided.

« […] whether it is Ladybug, Honeybee who calculate, here we know that we have Energy Plus behind, we have Radiance and so on, but basically, you never know how to open that black box, you never know if there are things that are incomprehensible when translating the results. »[13]

She insisted on the skills that people have to acquire in order to use computational design. According to her, there's two main issues: on one hand, the practice, the use of the tool, and on the other hand the interpretation of the results. She thinks there's a lot of opportunities, but without the right person to validate these two issues, no results can be obtained.[14]

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[11] *« Et donc du coup, sur un projet, on pourrait avoir un ambassadeur durable architecte ou un ambassadeur durable ingénieur stabilité, et donc voilà ça dépend de la personne, c'est un peu des couches qui se rajoutent. Mais oui le but serait vraiment d'intégrer ça dès le début de la conception, ce qui va permettre vraiment d'être sensible à la question. »*

[12] *« parce que Totem c'est aussi quelque chose qu'il faut savoir lire, comprendre et proposer des choses différentes donc parfois ici s'il y avait un moment donné du design computationnel, à faire des façades en fonction de l'étude de l'environnement, il faut savoir lire les quantités qui sont données. Il ne faut pas se dire « OK c'est rouge et donc là je mets une casquette où là c'est bleu et c'est OK » enfin il y a quand même quelque chose, il y a une granulométrie de connaissances à avoir. »*

[13] *« […] que ce soit Ladybug, Honeybee qui calculent voilà on sait que on a Energie plus derrière, on a Radiance et cetera, mais grosso modo on ne sait jamais ouvrir cette boîte noire, on ne sait jamais dire s'il y a des choses qui sont incompréhensibles dans la traduction de résultats. »*

[14] *« Je pense qu'il y a d'une part les pratiques, et il y a d'autre part la lecture des résultats. Et donc là il y a vraiment ces deux points-là pour moi qui doivent vraiment être pris en compte. Ça donne beaucoup d'opportunités, mais il faut que ces deux points-là soient validés pour que les opportunités soient remplies. »*

The actual tools are very limitative, for instance, in PEB, they need to encode the entire project, so they're limited by the quantity of data that they can reintegrate. She says: "*Either the tools are limitative, either their interoperability.*"

Sustainable generative design perception – Charlotte Dautremont

Barriers	Skills required to use the tool Skills required to understand the results Limitative tools Limited interoperability
Drivers	Can help in the decision process in the early stages of the design

Table 6 : Sustainable generative design perception: Charlotte Dautremont

Ideal toolset for sustainable generative design for Charlotte Dautremont (question 16)

According to Ch. Dautremont, collaboration is the basis of sustainable design. But the main issue, is the different levels of skills of the stakeholders. Someone can have an expertise in thermodynamics but no skills at all in computational design. [15] The stakeholders must be on an equal footing with the tool, so no one takes the advantages because of the skills required to use the tool. The tool must not add a challenge to the collaboration, which is actually the case most of the time, and she even says that the collaborative work must be made without computers.[16] Instead it must facilitate it to be truly useful. She also insists on the fact that the tools must be accessible in two ways: in their handling, and in the interpretation of the results. So the accessibility of a tool can either be a barrier.[17] She states:

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[15] *« […] je trouve que les outils aujourd'hui segmentent très fort, d'une part par leurs compétences [requises], où il faut savoir les utiliser Grasshopper, c'est pas tout le monde qui peut utiliser ça. En plus, il y a différents niveaux dans la compétence métier, donc un voilà un ingénieur en techniques spéciales va être très calé en thermodynamique, par contre ne vont peut-être pas du tout savoir modéliser, ou peut-être pas du tout savoir collaborer. […] Donc il y a différents niveaux de skills, je pense que ce c'est ça qui fait que les outils fonctionnent ou ne fonctionnent pas de manière collaborative, et pour moi […] si on veut vraiment faire de la durabilité sur un projet ça ne peut être que collaboratif on ne sait pas faire autrement en fait. »*

[16] *«[…] je pense que il faut des outils beaucoup plus collaboratifs. Beaucoup plus, beaucoup plus collaboratifs et quand je dis collaboratif c'est collaboratif ouvert. On n'est pas dans du séquentiel, je pense que ça doit vraiment […] un travail collaboratif en vrai donc sans ordi, ni tablette sans rien du tout. Là on pourrait vraiment faire dans la vraie collaboration selon moi. »*

[17] *« Donc l'outil, pour moi, peut être très bien, peut apporter énormément de choses, mais s'il est trop compliqué à prendre en main, à comprendre, parce qu'il y'a aussi prendre en main mais comprendre j'insiste là-dessus »*

« […] the tool must not add an additional level of difficulty. […] in the design process it is useless if the tool further complicates the situation, which is very much the case at the moment. I think there is a point where the tool, in fact, breaks down collaboration, and collaboration that is essential, which is major, which is crucial for a sustainable development of the project so if the tool is in fact a super sharp tool but one person in 100 knows how to use it, in fact it's useless. »[18]

Ideal toolset for sustainable generative design

Needs	Made for collaboration Easy to use Easy to understand

Table 7 : Ideal toolset for sustainable generative design: Charlotte Dautremont

[18] *« […] il ne faut pas que l'outil vienne rajouter un niveau de difficulté en plus. […] dans le processus de conception il est inutile si l'outil vient en plus compliquer la situation, ce qui est beaucoup le cas pour le moment. Je pense que là il y a un moment donné où l'outil, en fait, déforce la collaboration, et la collaboration qui est essentielle, qui est majeure, qui est cruciale pour un développement durable du projet donc si l'outil est en fait c'est un outil super pointu mais dont une personne sur 100 sait l'utiliser, en fait ça ne sert à rien. »*

2. Antoine MAES – A2M

Antoine Maes is an architect working as a parametric design specialist in A2m, an architectural design office in Bruxelles.

Antoine Maes – A2M	
Formation	- Master's degree in Architecture
Roles	- Parametric design specialist
Skills	- Parametric design

Table 8 : Profile of the interviewee: Antoine Maes

Sustainable design adoption at A2M (questions 3-4)

At A2M, sustainable design is applied mostly through the design of passive buildings, undertaken by a team of 3 thermic engineers, who have a dedicated role in the office.

Sustainable design is taken into account in two different ways, considering the phase of the project: the first one, during the first phases of the project, where "templates" have been put in place for good practice during the first approximations. The second phase, once the contest has been won, consists of getting certifications, like BREEAM and PEB, through calculations of thermal performances with tools like EES, PHPP, Wufy and Thermal. Totem has been used a few times on projects as well, and is assumed to be used during later stages of the design.

Sometimes, the sustainable design process can be very traditional. The architects draw a shape, with little to no idea if it will work, then the sustainable engineers make the project passive, with only small modifications.[19]

Sustainable design adoption : A2M	
Design stages	Detailed design Spacial coordination Technical design
Parts of the project	Energy systems - HVAC Enveloppe

[19] *«[…] parfois on a dessiné une forme, elle est jolie, aucune idée de si elle est bien ou pas, on va prendre ça et puis ensuite on va essayer de rendre ça passif ça c'est quelque chose qui arrive en ce moment oui c'est souvent quand même on part en fait des petites modifications dessus qui fait que ça c'est un peu plus facile mais voilà. Et donc parfois pour le gain de temps aussi on prend juste la forme tel qu'on l'a dessinée et on ne fait pas du tout de d'analyse. »*

Main objectives	Energy performances
Certifications	PEB BREEAM
Toolsets	EES Totem PHPP Wufy Thermal
Roles	**Dedicated** HVAC engineers

Table 9 : Sustainable design adoption: A2M

Computational design adoption at A2M (questions 5-6-7)

Parametric design is a strong focus for A. Maes. In the long run, the office wants to develop a department for parametric design, but for now, A. Maes works alone, and has a dedicated role as parametric design specialist.

At A2M, parametric design is used in two different ways:
The first use is for specific projects. Definitions will be created for a project depending on the demand. In this case, parametric design can be used during different stages of the design. It can be to draw geometry, as well as documenting prefab elements, or even run a solar analysis.

The second use is more for research and development purposes[20], where A. Maes puts in place routines to optimize the design process. These routines are made for non-expert users, and are used, for example, for data extraction. These routines are run by generalist architects, which don't have to use Grasshopper. They run the script directly from Rhino, and Grasshopper runs in the background.

The software used for parametric design are Rhino and Grasshopper, but also Revit and Rhino Inside. Some people use Dynamo at A2M, but not A. Maes. Concerning the different phases where the software are used, the office aims to use Rhino for the first phases, for the contests, and Revit afterwards. They do both simulation and optimization, but it's not business as usual. On the simulation side, it can be for solar, radiation, temperature, views and wind analysis. Optimization is done through plugins like Galapagos. According to A. Maes, he doesn't use

[20] *« Je dirais qu'il y a des interventions qui se font au niveau des projets donc ça, […] c'est des définitions qui sont vraiment créés pour un projet en fonction d'une demande particulière, […] et il y a aussi un aspect plus recherche le développement, où là j'essaie de mettre en place des outils qui qui pourraient être utilisés, […] qui pourrait même être utilisés par des personnes qui ne connaissent qu'un tout petit peu Grasshopper, en tout cas qui connaissent Rhino. »*

Octopus, made for multi-objective optimization, because he thinks that multi-objective optimization is not the solution[21].

Computational design adoption : A2M

Computational design type	Parametric
Design stages	Not specific
Parts of the project	Not specific
Main objectives	Data extraction Data implementation Geometry generation Analysis **Depends on the projects** Research & development
Toolsets	Rhino + Grasshopper Revit + Rhino Inside
Optimization	Optimization of the design process Simulation Optimization of the project
Roles	**Dedicated** Parametric design specialist

Table 10 : Computational design adoption: A2M

Computational design for sustainability adoption at A2M (questions 9 – 12)

When computational design is used for sustainable design it is applied for specific projects, and used for solar studies, during the tender phase. If A. Maes is integrated early enough in the design team, and if they can quantify the results[22], which is the critical condition according to him. They are actually conducting tests to try Grasshopper with Ladybug for solar studies, along with the sustainable design engineers.

One can note that A. Maes did not talk about Totem, even though he mentioned it when he talked about the use sustainable design in the office.

[21] *« En général, une optimisation se fait, ce qui est bien avec la multi-objectifs ça génère pas mal de propositions et l'architecte peut choisir. Après il y a des articles qui ont été publiés qui relèvent le fait que dans l'optimisation multi-objectifs, l'ordinateur ne s'en sort pas vraiment à optimiser de manière performante ou de manière juste, donc le mieux c'est d'optimiser par rapport à un seul critère. »*

[22] *« […] c'est ça qui est super important pour le design génératif, c'est qu'il faut réussir à mesurer en fait le design sinon ça va tourner en rond, donc voilà ça ne s'applique pas pour tout mais on peut en tout cas faire pas mal de choses. »*

Computational design for sustainability adoption: A2M	
Computational design type	Parametric Generative
Design stages	Tender
Parts of the project	Not specific
Main objectives	Solar studies LCA
Toolsets	Rhino + Grasshopper Ladybug Galapagos Totem
Optimization	Optimization of the project
Roles	**Integrated** Parametric design specialist

Table 11 : Computational design for sustainability adoption: A2M

Sustainable generative design perception for Antoine Maes (questions 13 – 15)

According to A. Maes, the main barriers are time and money, which are linked. He says time is the main barrier, even though he mentions more the fact that people are afraid to change their habits, especially in the computational domain. He says:
« […] I know that sometimes people who don't know [how to use the tool], tend to be suspicious, but then they don't know because they don't take the time to learn. So I'd really say time is the first barrier. »[23]

So even though it's not clearly expressed, one of the main barriers is how the architects perceive computational design, and the fact that they do not take the time to learn new things due to this psychological barrier. In fact, even if he creates small tools easy to use, they're only rarely used by the architects in the office.

He says that the use of generative design tools can also save time to the designers, but his opinion is mixed on this. On one hand, it can save time by raising the architect's awareness around sustainability, helping them learn from the different analysis launched over time, but this time saved is also taken during the learning phase, when the architects have to learn how

[23] *« […] je sais que parfois les personnes qui ne connaissent pas ont tendance à se méfier mais voilà après il ne connaissent pas parce qu'ils ne prennent pas le temps d'apprendre. Donc je dirais vraiment le temps c'est de la première le premier frein. »*

to use the tool. The time saved needs also to be compared to the time taken drawing a project and making it passive, keeping its initial shape.

It can help raise the architect's awareness around sustainability, but they will learn much more if the whole process isn't completely automated. To do so, sustainable generative design would be better applied for "manual generative design", where the designer chooses between different results, and modify one chosen result himself according to the results shown by the program[24].

He also mentioned that the difficulty is to have a tool capable of generating a shape vocabulary that we're satisfied with, without generating irrelevant geometries. One of the main advantages is the generation of shapes that we didn't think of.

Sustainable generative design perception – Antoine Maes

Barriers	People are afraid to change their habits and learn The difficulty to quantify results The definitions of the parameters to modify the shape of the geometry Very limited shape vocabulary Time consuming "parametric barrier" The cost
Drivers	Can be time saving Generation of shapes that we didn't think of Raising awareness

Table 12 : Sustainable generative design perception: Antoine Maes

Ideal toolset for sustainable generative design for Antoine Maes (question 16)

According to him, it depends to whom the tools are for. If it's for generalist architects, intuitive tools are a necessity. It needs to be intuitive in both ways: in the use of the tool and in the interpretation of the results. It also needs to be fast, with fast manipulations and fast analysis.

He says: *« Sometimes Ladybug will calculate things that we don't need for some studies and so Ladybug is great but we don't need all that information, so we'll rather do something ourselves, where we really use everything we need and so it can sometimes save a lot of time.*

[24] *« on a plusieurs gabarits et puis alors on voit les résultats et puis on teste mais parfois les résultats vont dire que cette partie du volume là est vraiment pas bonne pour tel critère et alors à ce moment-là la personne va modifier juste cette partie-là par exemple. »*

»[25] So, the fact that the tool computes only the information needed is also important, which means that one solution would be that the tool would let the user choose which analysis to perform. As he mentioned the very limited shape grammar offered by some tools, we can assume that a desired characteristic would be a large shape grammar.

A. Maes also cited an example to show the possible collaborations and the direction that can take generative design. He talked about building information generation, which is a concept developed by Front Inc. and applied on a Zaha Hadid Architect's project, City of Dreams Casino Hotel in Macau. They created a process by which BIM models are generated from an aggregation of functions that compute relationships between constituent parts. This process made possible the creation of an adaptable BIM model, which can preserve and generate design and construction data throughout the whole process. Something interesting about this process is that Front developed tools to dynamically pick up geometries from a reference model, and they can store and generate the information in the geometry, but the main flaw that A. Maes points out is:
« […] *it will allow [the information] to be sent in Revit but then it also means that if ever the model changes in one place, we can review all the codes and at the export level, it will redo a new export and the Revit will also be different […] it will be updated. However, if there is a problem with this type of model here, it is that if there is an amendment "here" and we are "there", then we have to go through all that again. »*[26]
Which means that since the information is stored in different models, a modification in one model means that the whole process needs to be reiterated. He also adds that the new version of the plugin that Front is developing will automate the whole workflow in the background.

Thus, we can note that even if A. Maes doesn't speak of this workflow as the ideal tool, some of its characteristics, such as the interoperability, the generation of the information, the targeting of the analysis to perform and the automation of the updates in the different models, meaning that the interoperability would be "seamless", seems important to him.

[25] *« Parfois Ladybug va calculer des choses que nous on n'a pas besoin pour certaines études et donc Ladybug c'est super mais on a pas besoin de toutes ces informations-là, alors on va plus faire nous-mêmes quelque chose où on utilise vraiment tout ce dont on a besoin et donc ça peut parfois faire gagner pas mal de temps. »*

[26] « *ça va permettre d'envoyer [les informations] dans Revit mais alors ça veut dire aussi que si jamais le modèle se modifie à un endroit on peut repasser tous les codes et au niveau de l'export, ça va refaire un nouvel export et le Revit sera différent aussi […] il sera mis à jour. Ça par contre s'il y a un problème avec ce type de de modèles ici, c'est que s'il y a une modification « ici » et qu'on est « là-bas » ben il faut repasser tout cela alors.* »

Ideal toolset for sustainable generative design	
Needs	Intuitive utilization Intuitive interpretation of the results Fast to use Seamless Interoperabiltiy Information generation Targets the analysis to perform Large shape grammar

Table 13 : Ideal toolset for sustainable generative design: Antoine Maes

3. Andy WATTS - Grimshaw

Andy Watts is the director of design technology at Grimshaw, in London. His background within architecture is in computational design, and he oversees computation, BIM, virtual and augmented reality. His team is a team of dedicated computational specialists or BIM specialists.

Andy Watts - Grimshaw	
Formation	- Master's degree in architecture
Roles	- Director of design technology - Computational design specialist
Skills	- Computational design - BIM - Virtual and augmented reality

Table 14 : Profile of the interviewee: Andy Watts

Sustainable design adoption at Grimshaw (questions 3-4)

At Grimshaw, the sustainability team works more on the overall strategy of the company and of the studio, than directly on projects. Instead, it's the department of design and technology who's in charge of the assessment of sustainability characteristics of projects. Most of the time, a consultancy office outside of Grimshaw will be in charge of the certifications, and the design technology team within Grimshaw will prepare the information needed, like for instance the daylight factor of a space. Usually, a computational design specialist will be in charge, alongside a BIM specialist for data extraction and implementation[27].

Regarding environmental design, Grasshopper with Ladybug and butterfly for solar assessments and wind analysis and day lightning is widely used, and sometimes by generalist architects with a bit of knowledge in Grasshopper, but mostly by the computational design team. Life cycle assessments are also being adopted, using One Click LCA, but it is still in the early stages of the adoption. A. Watts has not mentioned the phases of the project where LCA

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[27] *« Well, our sustainability team is not very hands on projects. They tend to be looking at the overall strategy of the company and of the studio. And then it's down to our design and technology team to be doing a lot of the hands on work, so there's still a bit of a gap there, and but then quite often the client will appoint somebody else outside of Grimshaw, who might be doing the BREEAM assessment or who might be doing the LEED assessment and those consultants will reach out to us and say "okay can you tell us what the daylight factor is for this particular space or whatever", at which point we will prepare those key pieces of information. »*

are performed but since it requires a high level of detail, we can assume that it is performed during later stages of the design, such as spacial coordination and technical design phases.

Sustainable design adoption: Grimshaw

Design stages	Detailed design Spacial coordination Technical design
Parts of the project	Not specific
Main objectives	Solar assessments Wind analysis Day lightning LCA
Certifications	BREEAM LEED
Toolsets	Ladybug Butterfly One Click LCA
Optimization	None
Roles	**Dedicated** Consultancy agencies **Integrated** Generalist architect Computational design specialist

Table 15 : Sustainable design adoption: Grimshaw

Computational design adoption at Grimshaw (questions 5-6-7)

At the start of a project, a design technology manager and a BIM manager will sit with the project leadership team to assess the aspirations of the project, and make a recommendation about the number of specialists and the time needed for the project[28].

As A. Watts says, the computational design specialists will intervene in multiple ways, depending on the needs of each project. They will undertake tasks like providing training to generalists architects as well as running analysis.

He states: « At which point the specialist will work with the architectural teams to help them deliver their work. That can be through, […] providing training and knowledge in Rhino and

[28] *« It will start to be determined by those early conversations about what do you want to do on your project. »*

Grasshopper at the very basic level and or it can be taking on some of the more complex tasks. Now that can include geometry generation, it can be analysis, whether it's environmental, whether it's geometric, whether it's spatial, right through to some very complex tasks around. »

4.1.1.1.1.1 Are you using computational design for simulation/evaluation or optimization?

It depends on the project, and what they're trying to achieve. A. Watts states: *« […] so, we will run simulation, […] it could be around pedestrian flow. It could be around environmental factors. It could be all of these things. […] but then we can take that a step further through to evaluation and actually generation to, you know, form feedback loops and start to optimise the design, whether that's manually or automatically. »*

In order to realize optimization, or even multi objective optimization, they use Galapagos and Wallacei. The optimization process is usually applied on geometry but they would like to do optimizations for the organization of spaces.

Computational design adoption : Grimshaw

Computational design type	Parametric Generative
Design stages	Early stages Tender
Parts of the project	Geometry
Main objectives	Geometry generation Environmental analysis Geometric, spatial analysis LCA **Depends on the project and its objectives**
Toolsets	Rhino + Grasshopper Galapagos Wallacei
Optimization	Optimization of the project
Roles	**Dedicated** BIM specialists Computational design specialists

Table 16 : Computational design adoption: Grimshaw

Computational design for sustainability adoption at Grimshaw (questions 9 – 12)

Since it's the computational design team that do a lot of the preparation for sustainability assessments in projects, tools like Ladybug and Butterfly for solar and wind analysis are widely used. Most of the time, the analysis will be runned by computational design specialists, but if the architect has knowledge in these tools, he runs the analysis himself. As mentioned in the Sustainable design adoption part, they also perform LCA.

The organization around computational design for sustainable design is the same than for computational design only, since it's the same stakeholders. Unfortunately, generative design has not been used for sustainability, so the use of computational design for sustainable design falls under parametric design for now.

Computational design for sustainability adoption: Grimshaw

Computational design type	Parametric
Design stages	Early stages Tender Spacial coordination Technical design
Parts of the project	Not specific
Main objectives	Solar analysis Wind analysis Daylight analysis LCA
Toolsets	Rhino + Grasshopper Ladybug Butterfly One Click LCA
Optimization	Optimization of the project
Roles	**Integrated** Generalist architects BIM specialists Computational design specialists

Table 17 : Computational design for sustainability adoption: Grimshaw

Sustainable generative design perception for Andy Watts (questions 13 – 15)

According to A. Watts, the main barrier is the adoption of sustainable design itself. The lack of sustainability knowledge among architects creates an issue in the integration of sustainability[29], making the process of the design linear instead of iterative. What they would want to do is having an iterative process, manually to begin with, then automating the whole process to create a computational loop. He states: *« […] it is actually already, let's say, manually creating the feedback loop, because at the moment people do the analysis and that's it, but what we would like people to be doing is running the analysis then thinking "OK, how do I change the design?" Once our design teams are thinking about that, let's say in a manual way, we can then start thinking about "OK, how can we automate that? How can that become this?" You know, computational loop. We're not there yet, and so I think there's a few steps to go through together. »*

We can also mention the fact that the sustainability team does not work directly on projects, and it can create a gap in the interpretation of the results for instance, since non-specialists are doing sustainability assessments. The lack of collaboration between different stakeholders and the lack of expertise in sustainable design can create issues in the different assessments.

Another barrier is the lack of time. The fact that they're still in a traditional design process, where they design the project and run a sustainability analysis, they don't have the time to go back and improve the project[30].

Finally, we can mention the skills needed to use the different software, and the fact that most of the time, such software enabling the user to make sustainable generative design for instance, are specialized in assessing one type of sustainability issue, so every time a new issue is addressed, the architects need to learn a completely new programme.

4.1.1.1.1.2 What opportunities would computational design for sustainable design offer according to you?

One of the main opportunities mentioned here is that computational design and the automation of the workflow would help to have a better integration of sustainability in the design process, and saving time, so that when they have a deadline, they would have already been able to take decisions around sustainability.[31]

We can also mention the fact that A. Watts talks about an analysis running in the background, which would imply that the need to learn how to use new tools and interpret them is also a big barrier in the adoption of sustainable generative design, which is also linked to the lack of time mentioned.

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[29] *« I think the barrier there is we need to get our architects thinking about sustainable design a lot more. That's probably a big knowledge gap within Grimshaw that we're trying to build up and then also you know I mentioned earlier the wider adoption, for instance of LCA. »*

[30] *« When we go through the design and then we run a sustainability analysis and then we don't have anymore time so there isn't really the time to think "OK, how do we go back and make this more sustainable? »*

[31] *« Computational design and automating that loop is going to allow us to be constantly iterating throughout the design process so that when we get to a deadline within, we've actually been able to enact some of those decisions to around sustainability. »*

Sustainable generative design perception – Andy Watts

Barriers	Adoption of sustainable design Lack of time to improve the project according to the results of the sustainability analysis Different software per assessment type Need to learn new tools and interpret them
Drivers	Time saving Iterative process

Table 18 : Sustainable generative design perception: Andy Watts

Ideal toolset for sustainable generative design for Andy Watts (question 16)

To avoid the barriers mentioned above, especially the issue of the different software to be learned by the architects, the ideal tool would be "passive", according to A. Watts[32]. Thus, by having such a program running in the background, the architects wouldn't have to learn new programs every time a new sustainability assessment is included in the design process, they would only see a dashboard showing them where they are[33]. Keeping the same platform is thus one of the biggest needs. It would also solve the adoption of sustainability in the general design process issue, by assessing the design automatically and giving feedback all along the design process. A. Watts states: *« if it's running in the background and it's automatic, […] we just need to make sure that people are structuring their design information in a particular way which is much easier to do, you know, most of our architects know how to use Revit as our BIM environment. All we're doing at that point is, let's say, tweaking how they use Revit rather than saying "here's this complete other programme that you now need to know how to use." »* We can note that though it hasn't been mentioned by A. Watts, one of the weaknesses of such a system would be the fact that the entire process is based on a software, so the designers would need to trust the system entirely.

Ideal toolset for sustainable generative design

Needs	Keeping the same computational environment Sustainability assessments running in the background

Table 19 : Ideal toolset for sustainable generative design: Andy Watts

[32] *« […] we talked about the LCA, that we want to be removing that as a manual or an active process and having it as a passive process »*
[33] *« So every night when the project team finish working, they come in the next morning they see a dashboard saying "this is where you are". »*

4.1.2 Summary per topic

4.1.2.1 Sustainable design adoption (questions 3 – 4)

Sustainable design adoption

	BSolutions	A2M	Grimshaw
Design stages	Detailed design	Detailed design	Detailed design
Parts of the project	Materials HVAC	Energy systems - HVAC Enveloppe	Not specific
Main objectives	Energy performance Energy systems Comfort LCA	Energy performances	Solar assessments Wind analysis Day lightning LCA
Certifications	PEB	PEB BREEAM	BREEAM LEED
Toolsets	PEB PMPP Design Builder Totem	EES Totem PHPP Wufy Thermal	Ladybug Butterfly One Click LCA
Optimization	Optimization of the project Optimization of the process	**Dedicated** Thermal engineers	None
Roles	**Dedicated** Architectural engineers Architects	**Dedicated** HVAC engineers	**Dedicated** Consultancy agencies **Integrated** Generalist architect Computational design specialist

Table 20 : Sustainable design adoption - per office

We can see in the Table 20 above that we have two different types of adoption. On one side, both Belgian offices have dedicated roles for sustainable design, and an approach centered mostly on energy. On the other hand, at Grimshaw, the adoption of sustainability throughout the design process is mostly undertaken by consultancy agencies that assess the project to get the certifications, and where generalists architects and computational design specialists work on giving the information needed to these agencies.

But the result is the same in the end. In the Belgian offices, the professionals dedicated to sustainable design are still working like a consultancy agency within the studio, and the design process is still very traditional: most of the time, the architects will design a project, then make it assessed by the different engineers or architects dedicated to sustainability, and the collaboration process will be limited to milestone meetings and validations. It tends to change, with a more collaborative process at the beginning of the design, helping taking more into account sustainability.

4.1.2.2 Computational design adoption (questions 5 – 7)

Computational design adoption

	BSolutions	A2M	Grimshaw
Computational design type	Parametric BIM	Parametric	Parametric Generative
Design stages	Detailed design Tender	Not specific	Early stages Tender
Parts of the project	Whole project	Not specific	Geometry
Main objectives	Data implementation Data recuperation	Data extraction Data implementation Geometry generation Analysis **Depends on the projects** Research & development	Geometry generation Environmental analysis Geometric, spatial analysis **Depends on the project and its objectives**
Toolsets	Revit Dynamo Totem	Rhino + Grasshopper Revit + Rhino Inside	Rhino + Grasshopper Galapagos Wallacei
Optimization	Optimization of the design process	Optimization of the design process Simulation Optimization of the project	Simulation Optimization of the project
Roles	**Dedicated** BIM Coordinator BIM Manager	**Dedicated** Parametric design specialist	**Dedicated** BIM specialists Computational design specialists

Table 21 : Computational design adoption - per office

Computational design adoption is more varied according to the offices. For instance, BSolutions has only a BIM team, which works mostly on data extraction and implementation. They also work on putting routines in place, so the architects can extract the data needed for the project.

At A2M, Antoine Maes is a parametric design specialist, and they tend to create a team in the office dedicated to parametric design. Here, the use of parametric design depends mostly on the project on which he works, where he will create definitions specific to the project. They also have research and development purposes where routines will be created to optimize the design process, but their use is not very established in the practice of generalist architects yet.

Then at Grimshaw, a much larger architect office, an entire department is dedicated to computational design, with a BIM team and a computational design specialist team. Here, computational design specialists have various tasks, depending on the objectives of each project. They can provide training to generalist architects, take on tasks such as simulations around pedestrian flow, run geometric analysis to even geometry generation.

It can be noted that the tasks of the computational design specialists are various and assessing the practice of computational design could be an entire master's thesis subject itself. Since the purposes of this work is to understand how sustainable generative design can be established in practices, and especially whom can perform such a design, this section helps us understand that computational design specialists can take an important part in sustainable generative design.

4.1.2.3 Computational design for sustainability adoption (questions 9 – 12)

Computational design for sustainability adoption

	BSolutions	**A2M**	**Grimshaw**
Computational design type	Parametric	Parametric Generative	Parametric
Design stages	Spacial coordination Technical design Tender	Spacial coordination Technical design Tender	Early stages Spacial coordination Technical design Tender
Parts of the project	Whole project	Not specific	Not specific
Main objectives	Data implementation Data recuperation LCA	Solar studies LCA	Solar analysis Wind analysis Daylight analysis LCA
Toolsets	Revit Totem Dynamo	Rhino + Grasshopper Ladybug Galapagos Totem	Rhino + Grasshopper Ladybug Butterfly One Click LCA

Optimization	Optimization of the design process	Optimization of the project	Optimization of the project
Roles	**Integrated roles** BIM Coordinator BIM Manager Generalist Architects Sustainability engineers	**Integrated** Parametric design specialist	**Integrated** Generalist architects BIM specialists Computational design specialists

Table 22 : Computational design for sustainability adoption - per office

Considering the adoption of computational design for sustainability, one can easily notice in Table 22 that in most of the cases, computational design is used through parametric design. We can assess two main objectives: the first one is the evaluation of the environmental impact and LCA of the project using Totem or One click LCA, alongside Revit and Dynamo; and the second one is doing microclimate analyses with solar, wind and daylight analysis. We can also observe that in every office, there's no dedicated role for computational design for sustainability. In most of the cases, it will be integrated in a role of computational design specialist or BIM specialist, with an exception at BSolutions where collaborative workshops are being put in place, with sustainability engineers taking part in the process as well. The tools used are either Revit alongside Dynamo or Rhino with Grasshopper, using plugins like Ladybug to perform microclimate analyses. These analyses are performed most of the time during tender phases. Regarding LCA, both Belgian offices use Totem, while the English office uses One Click LCA. Both tools are integrated in a workflow using Revit for data extraction. The LCA will be more likely assessed during later phases of the design, like spatial coordination and technical design phases since more detail is required to run these kind of analyses.

4.1.2.4 Barriers and drivers for sustainable generative design adoption (questions 13 – 15)

Sustainable generative design perception

	C. Dautremont	A. Maes	A. Watts
Barriers	Skills required to use the tool Skills required to understand the results Limitative tools Limited interoperability	People are afraid to change their habits and learn The difficulty to quantify results The definitions of the parameters to modify the shape of the geometry Very limited shape vocabulary Time consuming "parametric barrier" The cost	Adoption of sustainable design Lack of time to improve the project according to the results of the sustainability analysis Different software per assessment type Need to learn new tools and interpret them
Drivers	Can help in the decision process in the early stages of the design	Can be time saving Generation of shapes that we didn't think of Raising awareness around sustainability	Time saving Enhancing sustainability in projects

Table 23 : Sustainable generative design perception - per interviewee

Although expressed in different ways, a common barrier mentioned is the skills required to use the sustainable generative design tools, as well as the skills required to interpret them. The time needed to obtain these skills, and the psychological barrier that restrains the architects to learn such kind of skills (which is observed especially for computational skills, as mentioned by A. Maes) are the main reasons mentioned. According to A. Maes, the cost, which is linked to the time needed, is also a barrier in the adoption of SGD.

We can also emphasize that sustainable generative design requires both sustainability and generative design skills, which is generally not the case for the stakeholders. Usually, they will have an expertise in sustainable design or computational design, and in most of the cases a collaborative process between the different stakeholders is not established, thus creating a gap of knowledge.

Another problem mentioned by the Belgian interviewees is the limitations of the tools themselves. As Ch. Dautremont stated, the tools aren't useful if they add a challenge to the collaboration. The actual tools are also limitative in the shape vocabulary they offer, and the parameters that influence them, as mentioned by A. Maes. In fact, the definition of the parameters is itself a barrier, since one has to quantify the results he wants to obtain.

Regarding the drivers, two interviewees mentioned that it could save time. Ch. Dautremont stated that it could help taking decisions about sustainability in the early stages of the design, and A. Watts said that the iterative process created by the generative design would enhance the sustainability of the projects, completing the answer of Ch. Dautremont. A. Maes mentioned the fact that it could raise awareness around sustainability, which was discussed also by Ch. Dautremont as a necessity to create sustainable designs, but while Ch. Dautremont thinked of training the architects to have skills in sustainability, A. Maes believes that sustainable generative design could help the architects in getting those skills, especially if the process is not entirely automated, as he stated that the designer could choose between different results, and modify one chosen result according to the results shown by the program.

4.1.2.5 Needs and ideal toolset for sustainable generative design (question 16)

Ideal toolset for sustainable generative design

	C. Dautremont	A. Maes	A. Watts
Needs	Made for collaboration Easy to use Easy to understand	Intuitive utilization Intuitive interpretation of the results Fast to use Seamless interoperabiltiy Information generation Targets the analysis to perform Large shape grammar	Keeping the same computational environment Sustainability assessments running in the background

Table 24 - Ideal toolset for sustainable generative design - per interviewee

Since the use of the sustainable design tools were one of the biggest barriers to the adoption of SGD, we observed two types of solutions mentioned by the interviewees: the first one, mentioned by the Belgian interviewees, is the accessibility of the tool, either in its use and the understanding of the results. The second solution is provided by A. Watts, and consists of having the entire process running in the background to avoid training the architects and thus avoiding the learning gaps that might happen in the other case. It would also solve the time issue, where little to no time would be spent in the training process in both computational and sustainable design. One of the main flaws of this process is that the architects would have to trust the process and wouldn't be able to spot inconsistencies in the obtained results and know how to fix them.

A. Maes mentioned also some characteristics, such as short calculation time, the interoperability, the generation of information, the fact that it targets the different analysis to perform and the automation of the workflow, and Ch. Dautremont stated that the ideal tool would be a collaborative one. A. Watts mentioned that it would be better to keep the same computational environment, which is in line with the interoperability mentioned by A. Maes.

4.2 Spacemaker exploration

In this chapter, we will assess the tool with the highest score in the toolsets table (Table 1) which is Spacemaker, recently bought by Autodesk (Haukeland, 2019), since it has the best score according to the Table 1. We can also mention that this platform is clearly oriented towards sustainable studies, which is not the case for the other platforms, more feasibility studies-oriented.

To assess this tool, we will compare it to a computational workflow found in literature and to the needs mentioned in the interviews, and keep in mind that the purpose of this tool is for early stage planning, which means that the level of detail of the project is low, and therefore the analysis that can be performed doesn't need to be exactly accurate. The goal of Spacemaker is to help identify and fix problematic issues during early stage planning (Haukeland, 2019).

The first section of this chapter will present an overview of the different characteristics of the tool, such as the analysis performed and the geometries that can be generated, while the second and third sections will compare the toolset characteristics to the needs found in both literature and in practice.

4.2.1 Toolset overview

4.2.1.1 Interface

Workspace

Spacemaker allows the user to organize different **workplaces**, where different projects can be accessible to team members. There can be different workplaces, and members can have different roles, such as "viewers", "editors" and "admins", giving them different authorizations, such as editing projects for editors and admins and inviting new team members for admins only.

Project setup

To set up a new project, the user has to first locate its country and the site he wants to work on. Then, he can either select the site limits if the data is available in the country he works on, modify or draw the site limits. After that, the user has to specify a map area, where surrounding data will be added. The data available can be either the surrounding buildings, such as their height and property boundaries, but isn't necessarily free.

The user can then adjust and add information on the site and the surroundings, such as modifying site limits, the buildable area, the surrounding buildings, roads, rails, existing buildings on site, screens, terrain data, building pads, vegetation and view areas for view analysis.

Figure 14 : Spacemaker interface - project setup – adding information to the site and the surroundings

Surrounding or existing buildings can also be imported, in 2D or 3D, alongside with site limit properties or vegetation boundaries for instance. The supported formats are OBJ, IFC, DXF, JSON, or GML, or even images, imported in .png or .jpg as reference layers.Once the project has been setup, the user has access to three “modes”: Design, Analyze and Explore.

Design mode

The **Design mode** enables the user to draw a proposition, either manually or automatically with assisted design tools. The user can also import a design, whether it’s a geometry or a 2D design, in IFC, OBJ or DXF formats, but with a very basic detailing (Figure 15), such as basic volumes, stories/slabs, units without circulation and apartments including core layouts. Only simple extrusions of 2D footprints are supported by Spacemaker, which means that slopes, such as roofs, aren’t supported. We can also note that images in .png or .jpg formats can also be imported.

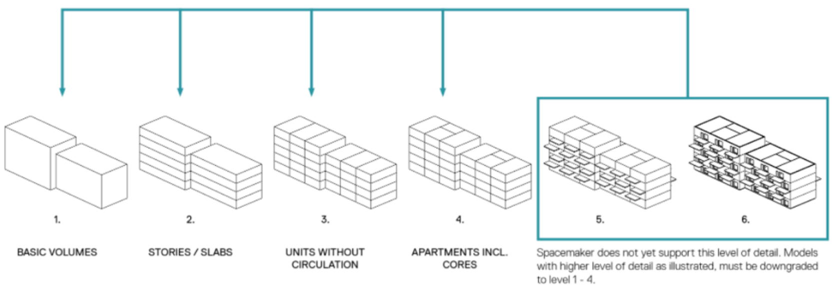

Figure 15 : Supported geometries (Source: https://help.spacemaker.ai/en/articles/4532077-supported-geometry)

The manual drawing tools (Figure 16) allows the user to draw a building, either from a line or a polygon. The automatic building tool will detect the site limits and generate buildings according to the typologies selected by the user. There are four typologies available actually: Lamellas; tower buildings; volumes; and city blocks. The volumes created are very simple and only a few variations, like the number of stories, the width of the building or the size of the units. The user can also assign a function to the units of the buildings, but for now the choice is limited to residential, apartment, core or commercial.

In design mode, some key figures are displayed and updated in real time. The user can also run a real time sun and noise analysis, to adapt directly his design accordingly. Some design constraints can also be added, like height boundaries; line buffers (polylines which the buildings must keep a certain distance from) facade buffers (the facades of buildings must keep a certain distance apart); facade distance (the facades of buildings must keep a certain distance apart).

Although very easy and fast to use, the volumes that Spacemaker allows the user to draw are not representative of the reality and can be very restrictive, even for early stage urban planning (Figure 15-16).

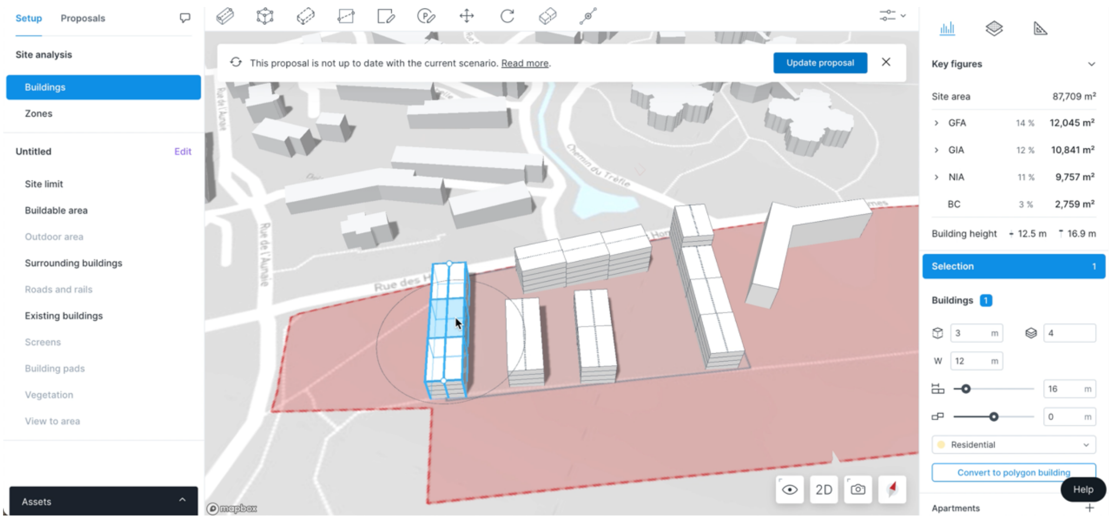

Figure 16 : Spacemaker interface - Design mode

Analyze mode

Once a first proposal has been sketched, the user can go to the **Analyze mode** (Figure 17) and run up to 13 types of analyses, which will be detailed later on.

Figure 17 : Spacemaker interface - Analyze mode

Explore mode

The **Explore mode** generates different propositions, according parameters defined by the user. These parameters are grouped under three categories: building properties, heights and apartment layouts.

In the **building properties tab (**Figure 19**)**, the user can change different parameters, such as function; building width, tower building dimension, division line width and layout types. The latter lets the user choose **layout patterns** to place buildings on the site. The different layout patterns available are in the number of 12, but the actual shapes of the buildings are limited to bars and towers with a flat roof, which doesn't offer a **shape grammar** suited for architecture.

Figure 18 : Different buildings layout types for generative design in Spacemaker (Source: https://help.spacemaker.ai/en/articles/4532976-generating-proposals)

The height settings let the user define a fixed number of stories or a height range to generate different height options, to optimize buildings according to one chosen “target quality”: sun, daylight or view. **The apartment layout settings** let the user choose between flexible units or custom unit mix. In the first option, the buildings will be given a layout based on their width and length. If the dimensions change enough, the layout will be replaced by one that fits the new dimensions better. In the latter option, the user inputs the desired distribution of apartment sizes for generated proposals. As well as in the Design mode, the different propositions have a **limited shape grammar**. Even though, the user is free to modify the generated proposals again in the “design” tab, and perform analyses as well.

Figure 19 : Spacemaker interface - Explore mode

Once the user has chosen its favorite designs between the propositions generated by Spacemaker, he can compare them in the “compare” section. It enables the user to have an overview of the analyses results of each chosen proposition, up to five proposals at a time.

The user can have further information by expanding some of the graphs, as seen in Figure 20 below. One can notice that all the analyses performed are not shown in the comparison tab, such as wind, comfort and microclimate, though important as well.

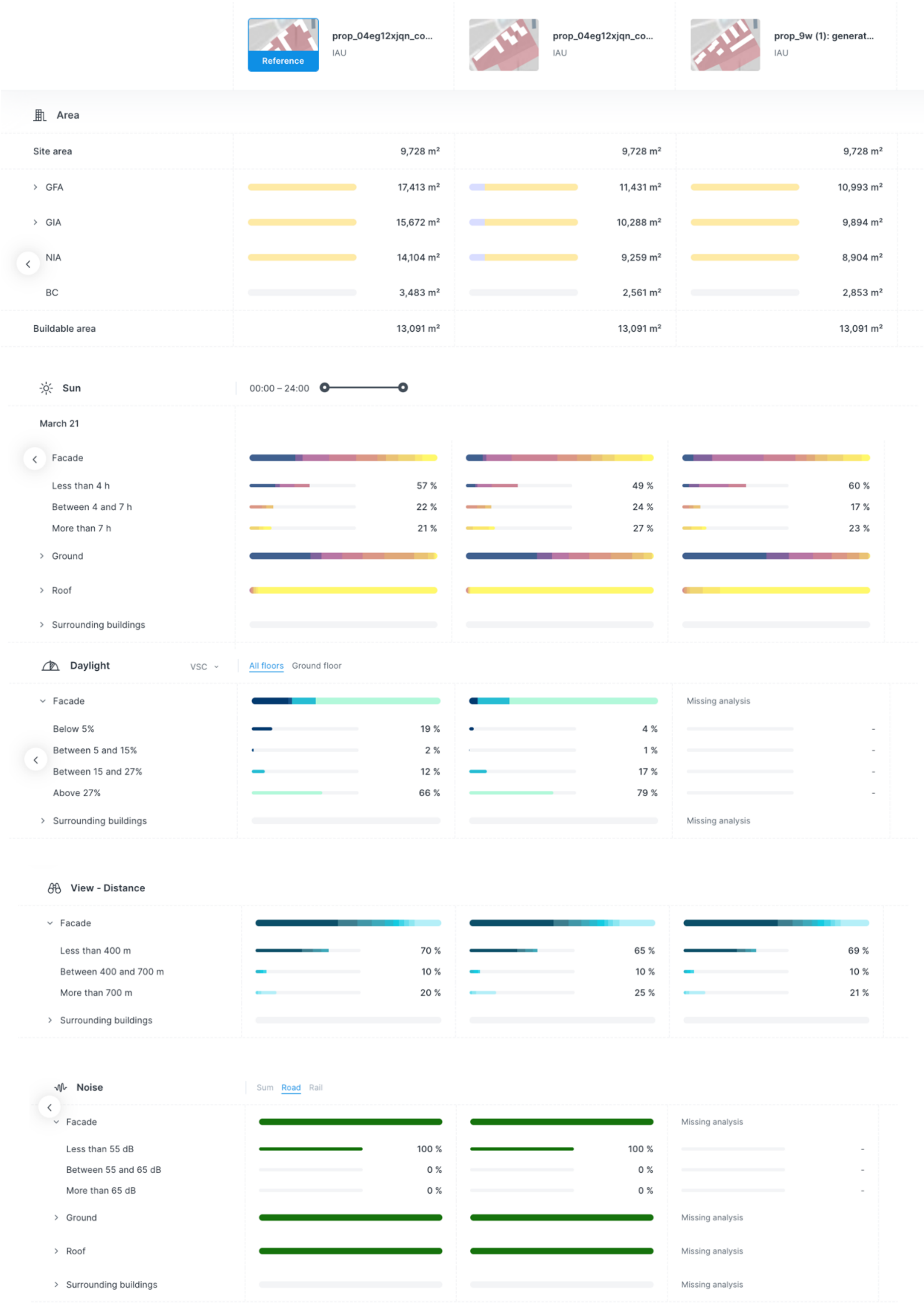

Figure 20 : Spacemaker comparison tab

Proposal geometries can be exported from Spacemaker to IFC or OBJ format, while statistics can be exported to Excel sheets. The proposals can also be opened as a revit model with an add-in, but it is still in development.

4.2.1.2 Analyses performed

The analysis performed by Spacemaker are various and easy to use within the limitation of simple geometries. The visual interface helps the non-expert to perform these analyses and understanding the different results.

Area analysis

The area analysis calculates multiple area metrics, such as:

Gross floor area (GFA)

Total area of all floors of the building;
All units are assumed to have only one story, which means the area is counted only once regardless of the height of the volume.

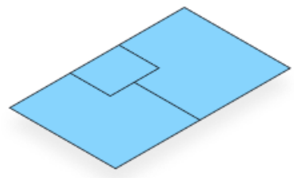

Figure 21 : GFA (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

Total gross internal area (Total GIA)

The total area of all floors within the external façades; It is calculated by multiplying GFA with a conversion factor that can be specified in the project settings.

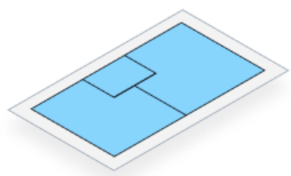

Figure 22 : Total GIA (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

GIA for one unit

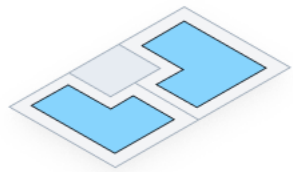

Figure 23 : GIA for one unit (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

Net internal area (NIA)

It is calculated by multiplying GIA with a conversion factor that can be specified in the project settings.

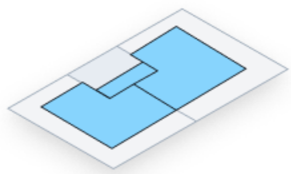

Figure 24 : Net internal area (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

NIA for one unit

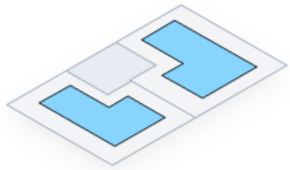

Figure 25 : NIA for one unit (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

Building coverage (BC)

It is calculated by summing the area of all building footprints. The calculation doesn't check if two buildings are overlapping, which means that volumes will be counted twice, resulting in biases in the values.

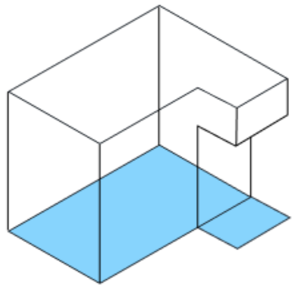

Figure 26 : Building coverage (Source: https://help.spacemaker.ai/en/articles/5373779-international-area-metrics)

Figure 27 : Spacemaker interface, with the area and building analysis results

All the area analysis figures are shown in the "analyze" window (Figure 27); and sorted by area functions.

Building analysis

- **Number of buildings**, where all connected volumes are assumed to be a part of the same building;
- **Facades: total area of all facades**;
- **Average number of stories**

- **Average terrain elevation**; to determine the building's height

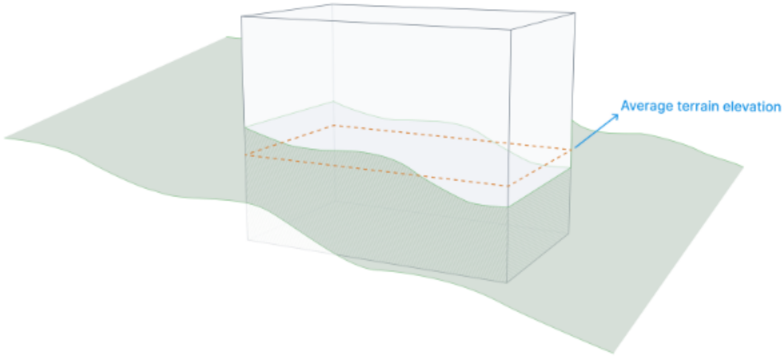

Figure 28 : Average terrain elevation (Source: https://help.spacemaker.ai/en/articles/4532050-building-heights)

- **Maximum building height**
  The maximum building height is measured from the average building height, to the highest point of the building.

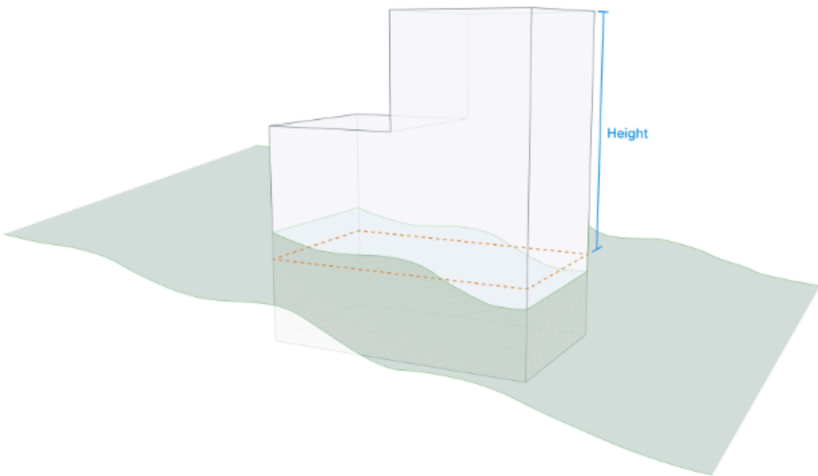

Figure 29 : Maximum building height (Source: https://help.spacemaker.ai/en/articles/4532050-building-heights)

- **Average building height**

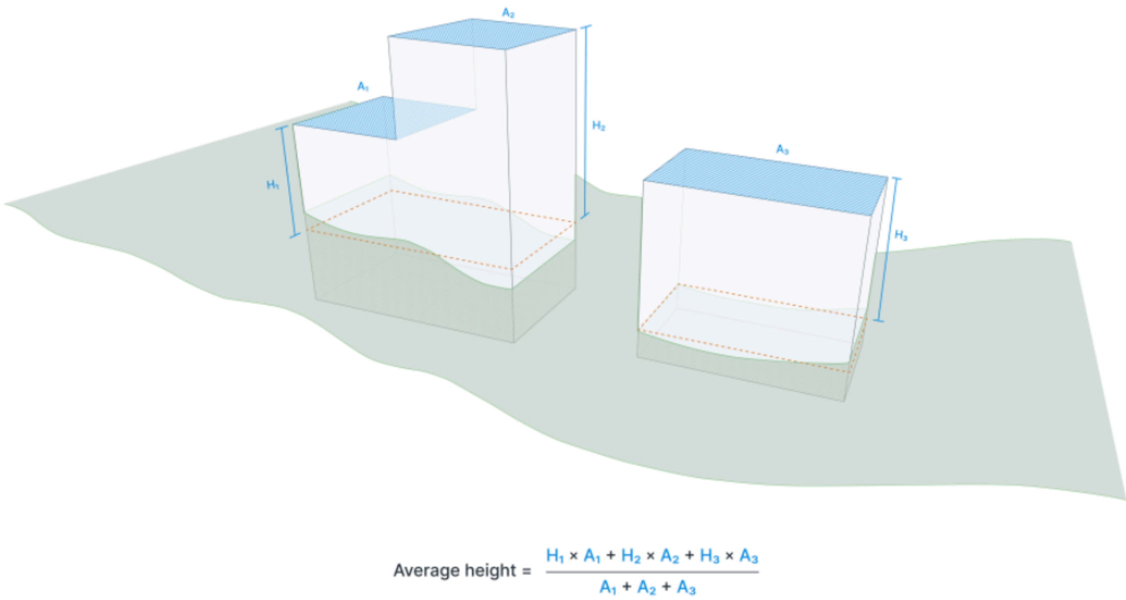

Figure 30 : Average building height (Source: https://help.spacemaker.ai/en/articles/4532050-building-heights)

The average building height is a weighted average of all building heights. The weighting is determined by the proportion of building area with a given height, which means that the larger the footprint of a building, the higher the weight.

Building analysis is shown the same way as area analysis, in the same window, where key figures are displayed.

Daylight analysis – obstruction angle

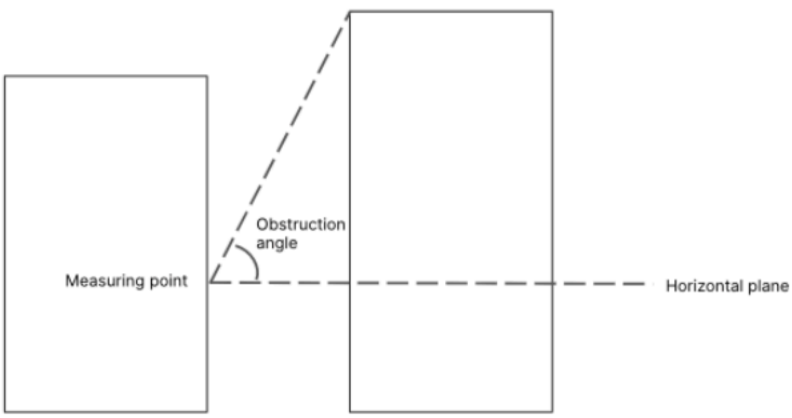

Figure 31 : Obstruction angle (Source: https://help.spacemaker.ai/en/articles/4554476-obstruction-angle-analysis)

Obstruction angle (Figure 31) is defined as *"the maximum angular altitude of the top of any obstruction of view towards the horizon, measured from a point on a facade in the plane* *perpendicular to the facade. The obstruction angle analysis is thus calculated from the horizon and up and will register the lowest angle with unobstructed view of the sky."* (Haukeland, 2019)

Here, Spacemaker doesn't take into account overhanging volumes, such as balconies, in the calculation, even though they can have a significant impact on daylight conditions. Furthermore, this analysis considers obstructions interfering only in the perpendicular plane out from the facade, regardless of, for instance, the impact an angled facade.

Figure 32 : Spacemaker interface, with Daylight analysis (obstruction angle) displayed

The daylight analysis is displayed in both ways: First, in a graphic way to show problematic facades, then in key figures on the "analyze" window (Figure 32).

Daylight analysis – vertical sky component

Vertical sky component is also a daylight analysis. It is computed at different points on the façade, and "measure how much each point is illuminated from the sky" (Figure 33).
It is defined as "*the ratio of the vertical sky-diffuse illuminance to the unobstructed horizontal sky-diffuse illuminance*" (Li, et al., 2013).

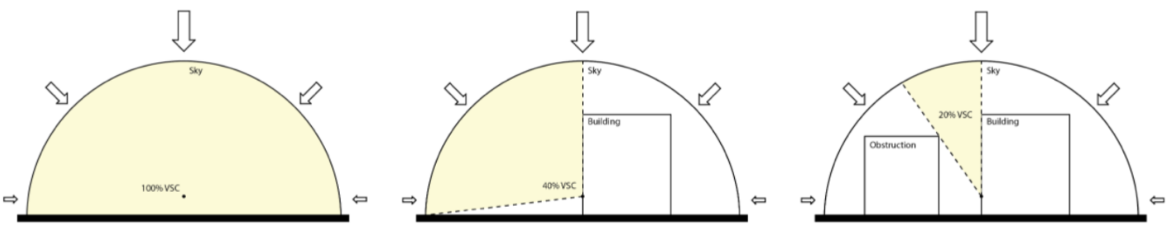

Figure 33 : Vertical sky component (Source: https://help.spacemaker.ai/en/articles/4532005-vertical-sky-component-analysis)

Even though VSC only measures the direct light from the sky on façades, without taking into account window sizes, building materials, room sizes or room functions; it is still a good early predictor for daylight potential and its use in early stage design is relevant.

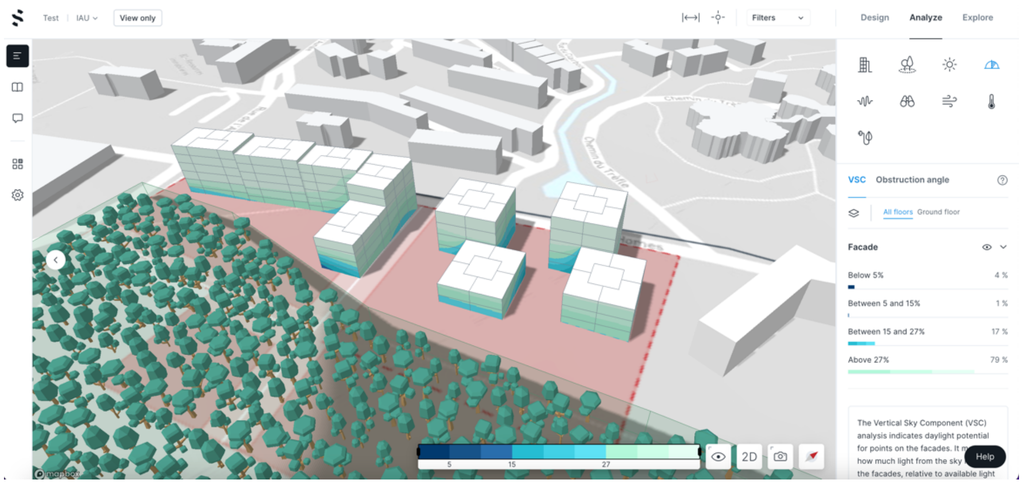

Figure 34 : Spacemaker interface with Daylight analysis (VSC) displayed

As for obstruction angle, a graphic showing the percentage is directly displayed on the façade, with key figures in the “analyze” window (Figure 35).

Noise analysis

Noise analysis in Spacemaker are based on the Common Noise Assessment Methods developed by the European Commission (CNOSSOS-EU) and the ISO standard ISO 17534-4. It handles noise from road traffic and railways, and calculates the long-term day-evening-night average noise level **Lden**, which is not directly linked to the sound level since a penalty is added during the evening and night.

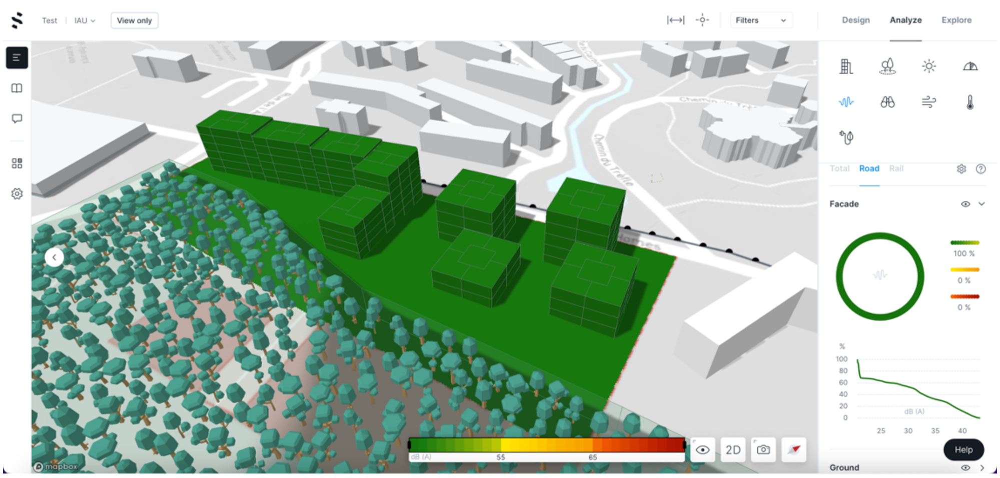

Figure 35 : Spacemaker interface with noise analysis displayed

Noise is displayed on both view and key figures. Here, the user can have an indication on the sound level, measure in dBA, on both site and buildings (Figure 35).

Outdoor area analysis

Outdoor area is analyzed in Spacemaker according to “quality targets” defined in the project parameters. These quality targets are in the number of five:

- Amount of outdoor area

It is defined as percentage of GIA for residential functions and can be modified in project settings.

- Noise conditions

The user can define a noise threshold, so that the areas with higher decibel values are filtered out.

- Terrain steepness

This target filters out areas with a steepness higher than 1:3 meters, but it can also be displayed in more detail.

- Spaciousness norm – specific to Oslo, Norway

This norm is specific to regulations in Oslo, and therefore is not automatically available in other countries. It suggests a minimum distance between buildings relative to their height to ensure light and feeling of spaciousness to the outdoor areas.

- Sun conditions

The sun target refers to the user defined number of hours that a certain proportion of the outdoor area must be sunlit for a given date within a given time interval.

Figure 36 : Spacemaker interface with Outdoor area analysis displayed

In Spacemaker interface (Figure 36), the user can toggle the noise and steepness (and spaciousness if calculated) to show which parts of the terrain fit in these criteria, with its area shown in the analysis tab. A graph showing the sunlit area per hour of the day on a given date and timeframe is also displayed in the analysis tab.

Sun analysis

Sun analysis in Spacemaker consists of computing the number of sunlit hours on different surfaces of the project, such as the ground, roofs and facades. Sun hours are calculated using the sun position with respect to the site location. The sun hours are computed using ray tracing technology, where rays are traced from each measuring point in the direction of the sun. These points are placed on a grid for both volumes and terrain.

The sunlit hours are computed following a determined date, without taking into account the presence of clouds in the sky. The fact that the results are displayed using graphs with an approximation of one hour can be discussed, but its use for early stage planning is still relevant.

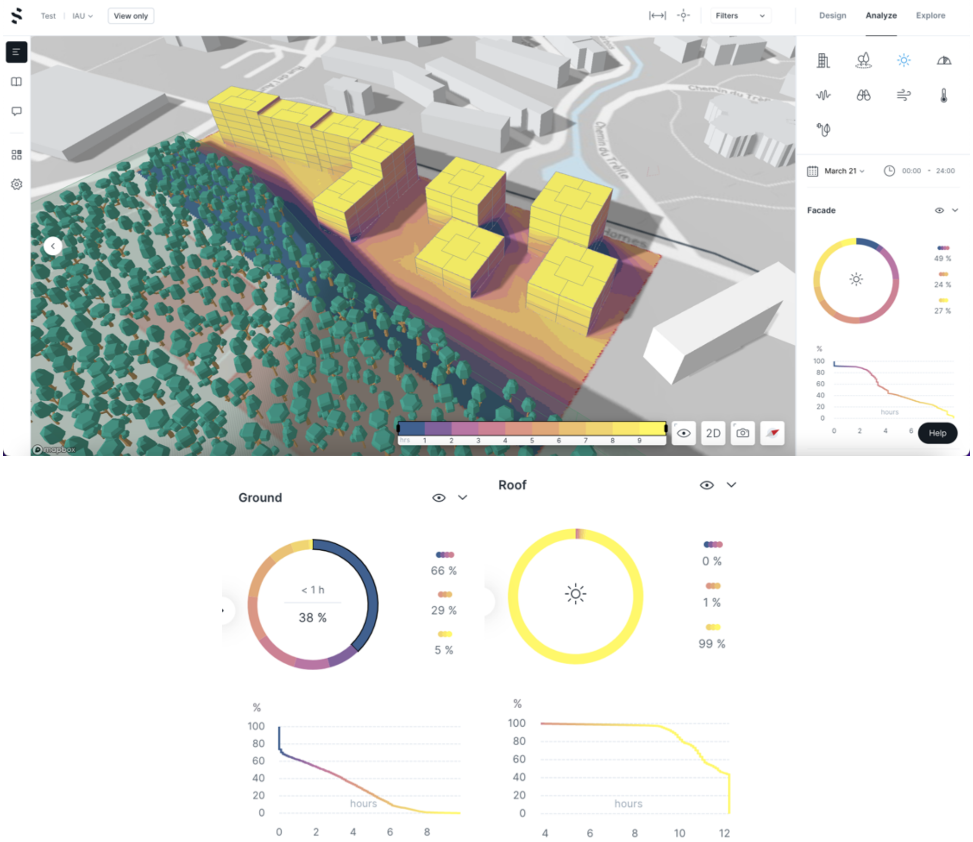

Figure 37 : Spacemaker interface with sun analysis displayed

The number of sunlit hours is displayed on the terrain, but also on the façades and roofs of the buildings. Some key figures are displayed in the analysis tab, with interactive graphs showing the percentage of each chosen surface given by number of sunlit hours, and displayed according to the nature of the surface: facade, roof or ground (Figure 37).

View analysis

- **View to area**

The view to area metric is related to an area of interest defined by the user, where lines are drawn between target points on the area of interest and observation points on the façade (Figure 38).
"A line that hits the area is defined as a line that does not intersect with any other objects on the way from the facade to the area. If there is at least one hitting line from the observation point, we say that the observer can see the area of interest from that point." (Haukeland, 2019)

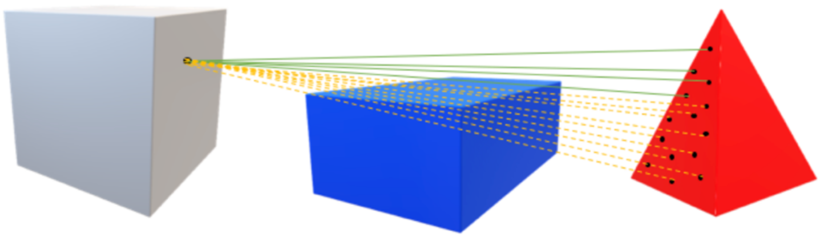

Figure 38 : View to area analysis concept (Source: https://help.spacemaker.ai/en/articles/4531949-view-to-area-analysis)

Figure 39 : Spacemaker interface with view to area displayed

The surface on the façades with a direct view on the point of interest are shown in green. On the analysis tab, we can also see the percentage of façade with a view (Figure 39).

- **View distance**

The view distance analysis gives an indication on how distant the view is from a chosen point on the façade. It is calculated by measuring the average view length across a 120 degrees horizontal field of view from a point on the façade (Figure 40). If the rays are interrupted by surrounding buildings or terrain, it reduces the average view distance from the given point.

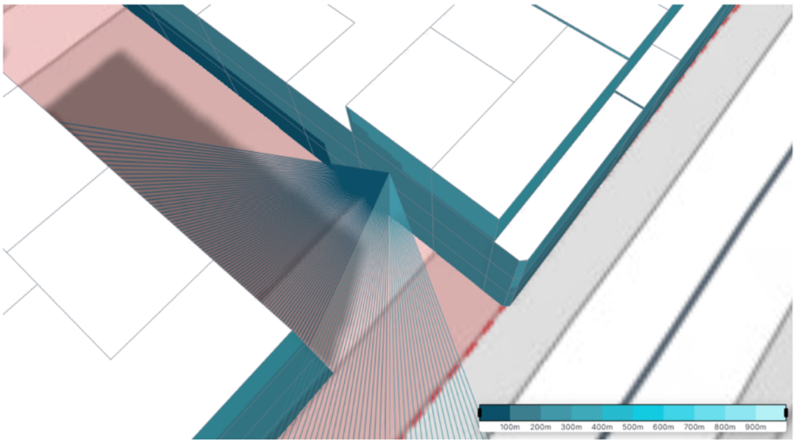

Figure 40 : View distance analysis rays (Source: https://help.spacemaker.ai/en/articles/4531960-view-distance-analysis)

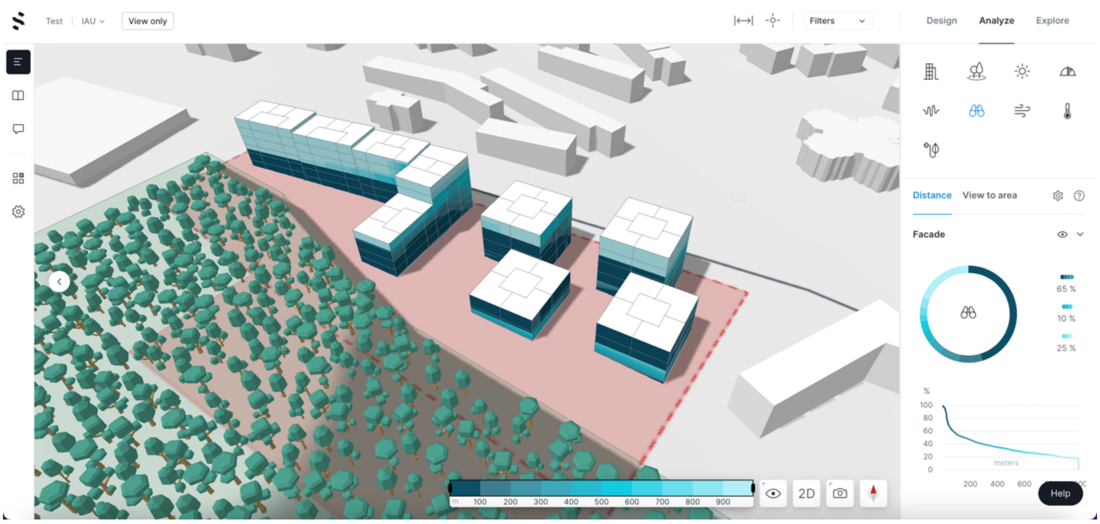

Figure 41 : Spacemaker interface with vew to distance displayed

As for view to area analysis, the results are displayed graphically on the buildings, and some key figures are available in the analysis tab (Figure 41).

Wind analysis

Spacemaker's wind analysis is based on several models and sources, such as 3D computational fluid dynamics (CFD), OpenFOAM, Steady-state RANS, k-Epsilon turbulence model, Global Wind Atlas and ERA5.

Spacemaker assesses both **wind speed** and **pedestrian wind comfort**, and followed the recommendations in the London guidelines on local wind analyses using CFD (computational fluid dynamics). The CFD are calculated through the open source computational tool OpenFOAM. As a comparison, Butterfly from Ladybug tools uses OpenFOAM as well, and they say on their website that *"At the present time, OpenFOAM is the most rigorously-validated* *open source CFD engine in existence and is capable of running several advanced simulations and turbulence models"* (Sadeghipour Roudsari & Mackey, 2013). They also use the realizable k-Epsilon turbulence model, as encouraged by the London guidelines. *"Turbulence modelling is a research field in itself, but this model is believed to give reasonable results for the case of urban wind simulations."* (Haukeland, 2019)

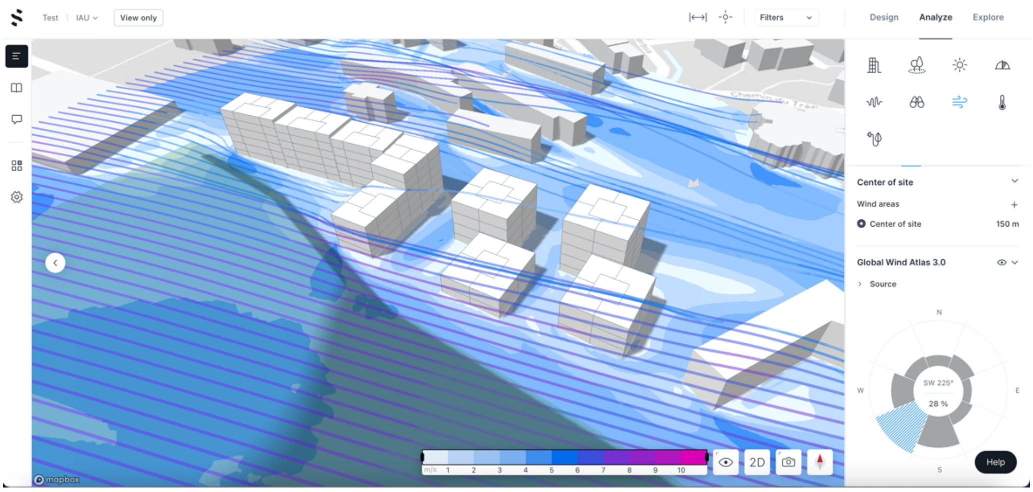

Figure 42 : Spacemaker interface with wind analysis displayed

The interface shows the wind speed on the site, depending on the direction of the wind as seen in the analyze tab. By default, the wind speed displayed are corresponding to the main direction of the wind, but the user can choose to display the graphs associated to other wind directions (Figure 42).

Considering **wind comfort**, Spacemaker has its own "comfort scale", based on a chosen reference (Figure 43). By default, the Lawson LDDC scale is chosen as reference, based on the recommendations for the city of London. But this scale might not be suited for windier places, or warmer climates, and can be changed in the project parameters.

	Sitting	Standing	Strolling	Walking
Lawson	1.8 m/s, 2%	3.6 m/s, 2%	5.3 m/s, 2%	7.6 m/s, 2%
Lawson 2001	4.0 m/s, 5%	6.0 m/s, 5%	8.0 m/s, 5%	10 m/s, 5%
Lawson LDDC	2.5 m/s, 5%	4.0 m/s, 5%	6.0 m/s, 5%	8.0 m/s, 5%
Davenport	3.6 m/s, 1.5%	5.3 m/s, 1.5%	7.6 m/s, 1.5%	9.8 m/s, 1.5%
NEN 8100	5 m/s, 2.5%	5 m/s, 5.0%	5 m/s, 10%	5 m/s, 15%
CSTB	3.6 m/s, 5%	3.6 m/s, 5%	3.6 m/s, 10%	3.6 m/s, 20%

Figure 43 : Spacemaker wind comfort scale compared to reference comfort scales (Source: https://help.spacemaker.ai/en/articles/4611552-pedestrian-wind-comfort)

Here, Spacemaker displays wind comfort through 4 categories: “sitting”, “standing”, “strolling” and “walking”. On the table above, we can see the different values of each category according to each reference scale. After having runned the analysis, the values are displayed graphically so the user can directly see which area of the project may be problematic (Figure 44).

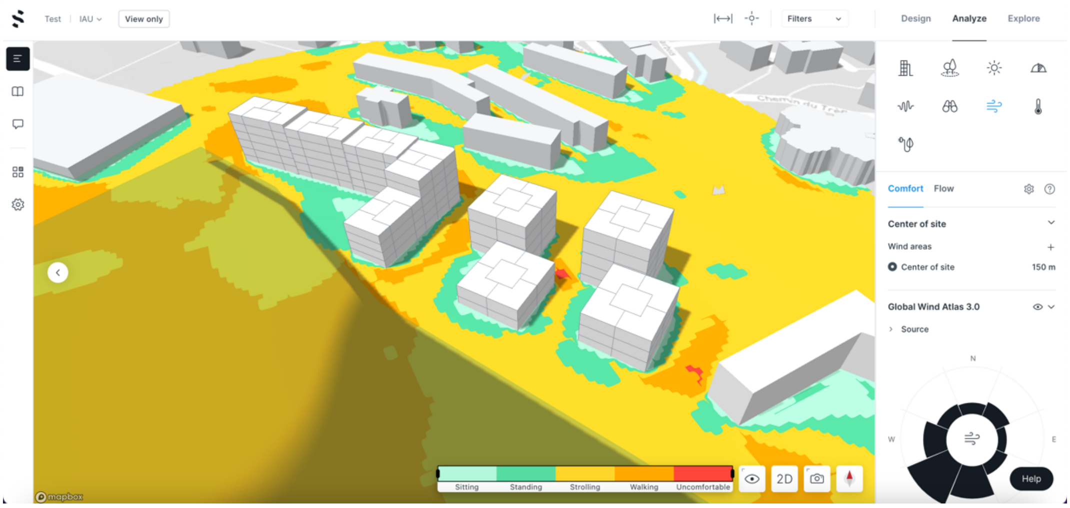

Figure 44 : Spacemaker interface with pedestrian comfort displayed

Microclimate analysis

Microclimate analysis aims to let the user evaluate outdoor thermal comfort on a chosen site. It combines our sun, wind, and daylight analyses with historic weather data to create a comprehensive microclimate map of the site, and is based on the Universal Thermal Climate Index (UTCI) to evaluate the perceived temperatures. The weather data includes information about solar radiation, cloud cover, and winds, all from the ERA5 dataset provided by the Copernicus Climate Change Service. Microclimate analysis is divided in two sections: Temperature percentiles and comfort frequency.

In the **Temperature percentile** section, the user is able to view the typical perceived temperature (50th percentile), the warmest (95th percentile), or the coldest (5th percentile) on a chosen time, date and climate, which is displayed on the 3D view on the site, with the percentage of the area in the comfortable range displayed in an interactive graph (Figure 45).

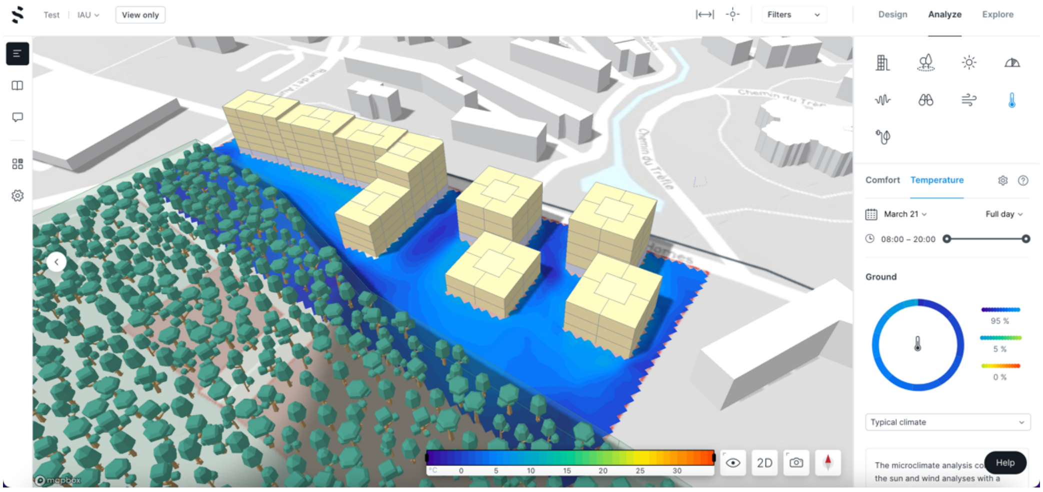

Figure 45 : Spacemaker interface with temperature percentile displayed

Considering **comfort frequency**, it computes the frequency at which the perceived temperature is within the chosen comfortable range. Following the London guidelines for assessing comfort, the default range is 0 to 32 degrees Celsius, but it can be changed in the project settings. As for temperature percentile, the data is displayed in the 3D view showing the areas with the different results, with an interactive graph showing the percentage of area under the percentage threshold (Figure 46). Actually, the ground type and building materials are not yet taken into account in the calculations, though having a significant impact on the ground temperature.

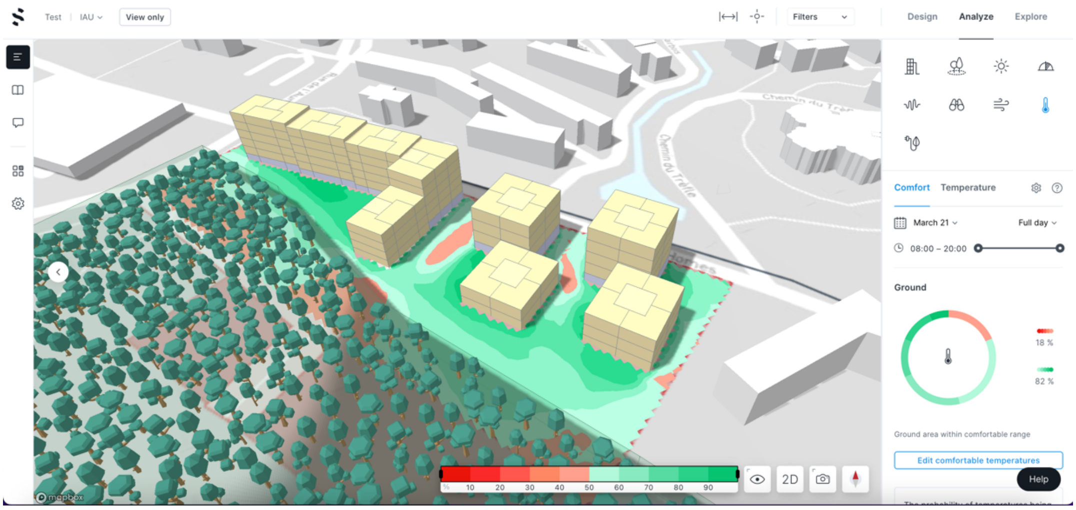

Figure 46 : Spacemaker interface with comfort frequency displayed

Solar panel analysis

This analysis assesses the **potential** of the site for **solar panel electricity generation**. It uses sun analysis as a foundation, calculating sun maps on a 1m x 1m grid for all roofs for each hour of the year. The data comes from the Copernicus database, and the Sandia Simple Sky Diffuse model is used. By default, the solar panel efficiency is of 15%, the power of 300W or 150 W/m2, the azimuth at the south, the angle at 0 (or horizontal), the roof coverage of 60% and the system losses of 14.08%. The user is free to change these parameters according to the data he has for its photovoltaic panels.

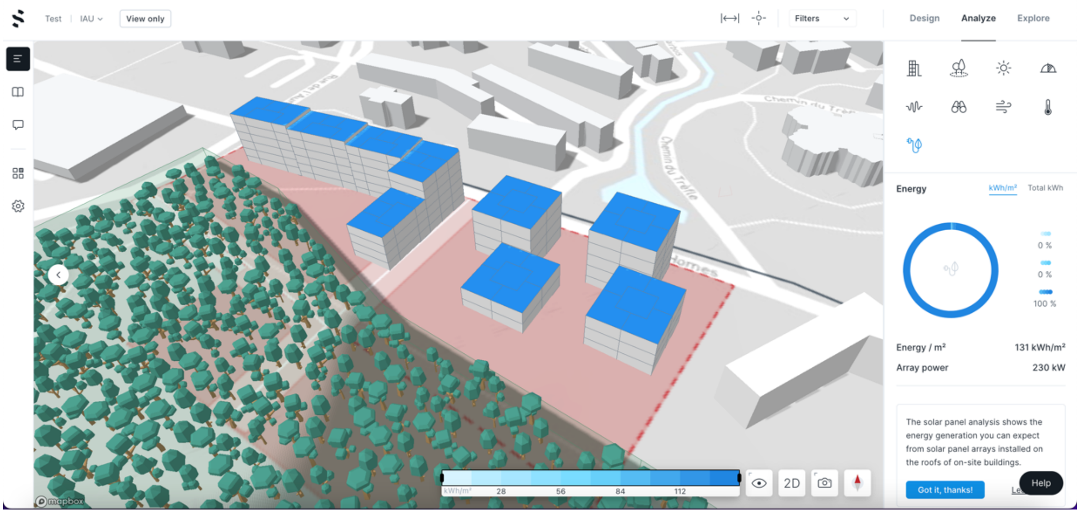

Figure 47 : Spacemaker interface with solar energy analysis displayed

The analysis has three outputs: kWh/m2/year; kWh/roof/year; and kW/roof. The values are displayed graphically on the roofs of the buildings assessed, and key figures are shown in the analyze tab (Figure 47).

4.2.1.3 Comparison with the results of the toolset exploration

When comparing the characteristics of Spacemaker to the toolsets table (Table 1), we noticed that most of the information was confirmed, with the exception of the solar panel analysis which wasn't mentioned in the website's main page. We also corrected the lack of information regarding the design stages where Spacemaker is supposed to be used. Regarding the scale where the platform can be used, we've seen that the shape grammar it offers isn't suited for architecture. Thus, we've corrected it to be useful only for urbanism.
All the corrections made can be seen in red in the Table 25 below. We can also mention that the score of Spacemaker has increased, consolidating our choice to assess this platform.

Applications	Software	Grasshopper + Galapagos/Octopus				Testfit	Hypar**	Spacemaker	PRISM	Archistar
		Ladybug	Honeybee	Butterfly	Dragonfly					
Scale	Building	x	x	x	0	x	x	0	x	x
	Urban	x	0	/	x	x	/	x	x	x
Design stage	Early	x	0	0	x	x	x	x	x	x
	Mid	/	x	/	/	/	x	0	/	
	Later	0	x	x	/	0	0	0	0	0
Creation	Districts	0	0	0	x	x	/	x	x	x
	Buildings	0	0	0	x	x	x	x	x	x
Analysis	Area	0	0	0	0	x	/	xx	x	x
	Cost	0	0	0	0	x	/	0	0	x
	Building type	0	0	0	0	x	x	xxx	xxx	x
	Building height	0	0	0	0	x	x	x	x	x
	Topography	0	0	0	0	x	/	x	0	0
	Daylight	x	x	0	0	0	x	x	0	0
	Noise	0	0	0	0	0	/	x	0	0
	Shadow	xx	0	0	0	0	x	x	0	x
	Sun	xxx	x	0	0	0	x	x	0	x
	View	x	x	0	0	0	x	x	0	0
	Wind	0	0	x	0	0	/	x	0	x
	Energy use	0	xx	0	xxx	0	/	0	0	0
	Climate	x	0	0	x	0	/	0	0	0
	HVAC	0	x	x	0	0	/	0	0	0
	Energy potential of the site	x	0	0	x	0	/	x	0	0
	Thermal comfort	xx	x	x	0	0	/	x	0	0
Score		11	7	3	5	5	6	15	5	7
Analysis type	Advanced	/	x	x	/	0	0	0	0	0
	Fast	x	0	0	x	x	x	x	x	x
Community-supported		x	x	x	x	0	x	/	/	/
Flexibility*		x	x	x	x	/	x	0	/	x
Accessible to non-specialists		0	0	0	0	x	x	x	x	x

Table 25 : Toolset exploration - corrected

4.2.1.4 Limitations

One of the main limitations of the toolset overview is the absence of comparison of the analysis provided by Spacemaker with another simulation tool. The results obtained via Spacemaker must be considered with caution, even with the transparency of the platform regarding the analysis provided.

5 Discussion & research limits

In this chapter, we're going to try to answer the research questions asked in the methodology, and compare the results obtained to the results of the state of the art.

5.1 How is SGD established in practices?

During the state of the art and the interviews, we have seen that SGD is not yet fully established in practices (section 2.2). Indeed, we have seen that only few practices are using generative design for sustainable design, and even in these practices, it was only in the early stages of the adoption. In fact, even though computational design is being used for sustainable design, in most practices it is used through parametric design instead of generative design. In this section, we will have an overlook at the results that we've obtained, and assess the establishment in each indicator, such as shown in Figure 7 in section3.1.

5.1.1 Design stages, main objectives and parts of the project

The integration of computational design for sustainable design in practices comes during two **design stages**: in **early stage design**, during tender phases, mostly for solar assessments; and in the **later design stages**, for LCA analysis since it requires a high level of detail. The use of computational design for sustainable design is still in the early stages of the adoption, and used mostly **to solve specific issues in projects**.

Regarding the **objectives** of the use of SGD in literature, the lack of consensus on the parameters to evaluate sustainability in the designs has contributed to a lack of computational frameworks assessing sustainability issues, thus being used only in a project-oriented way, most of the time to optimize one sustainability criterion. Nevertheless, the most recurring analyses in literature (section 2.2.2.2) were oriented on energy systems and microclimate, with parameters such as solar access, solar radiation, wind flows or outdoor comfort.

In practice, the main objectives of the use of computational design for sustainable design are LCA, which was the most recurring objective with all the interviewees mentioning it, then Solar analysis, with two practices assessing it, and then Daylight and wind analyses, only performed at Grimshaw (section 4.1.1). Even though these parameters are assessed mostly through parametric design, we can assume that SGD will be used to optimize the same parameters.

While solar, daylight and wind analyses are expected to be used in practices, we can notice that LCA is not mentioned in literature regarding the use of generative design for sustainable design. Such bias can come from the fact that the keywords used to search the articles were linked to generative design, not parametric, and LCA in practice is done exclusively through parametric design or other computational methods, such as BIM.

5.1.2 Toolsets & optimization process

Considering the **toolsets** used for SGD, we have seen in literature that there was no dedicated tool (section 2.3.3). Instead, tools like Grasshopper and Dynamo were mostly used, and sometimes the researchers would create their own generative design tool to meet their needs, because of the lack of existing specialized tools. Hence, the use of Grasshopper and Dynamo in practices was not a surprise (section4.1.2.3). These tools were used alongside plugins, such as Ladybug or Butterfly for Grasshopper and Totem in the Belgian offices, alongside Revit and Dynamo.

As for the **optimization process**, since most of the cases where generative design was used for sustainable design were focused on optimizing a single criterion instead of doing multi-criteria analyses, we expected the use of SGD to be the same in practice. Since computational design for sustainable design is mostly used through parametric design, there was no optimization process regarding the sustainability parameters. The only optimization process encountered in practices would be manual, not automatic, to modify the project manually to meet the results wanted.

5.1.3 Roles and skills associated to SGD

In the state of the art, we assumed that **dedicated roles** to SGD weren't likely to be widespread, with instead experts in generative design working on SGD in projects since it requires a developed skillset in generative design to use the available tools. We assumed the roles of the stakeholders were: generative design experts; sustainable design experts or architects, as shown in Figure 4.

During the interviews, we've seen that even in large practices such as Grimshaw, there was no dedicated role to generative design alone, thus SGD being even more *niche*, no dedicated role to SGD. Instead, most of the time computational design specialists where undertaking computational design for sustainable design, and sometimes BIM specialists as well. We can notice that collaborative processes are not widespread in day-to-day practice, with an exception at BSolution where Ch. Dautremont has been putting in place workshops to integrate sustainability in the early stages of the design, integrating sustainability experts in the design process as well.

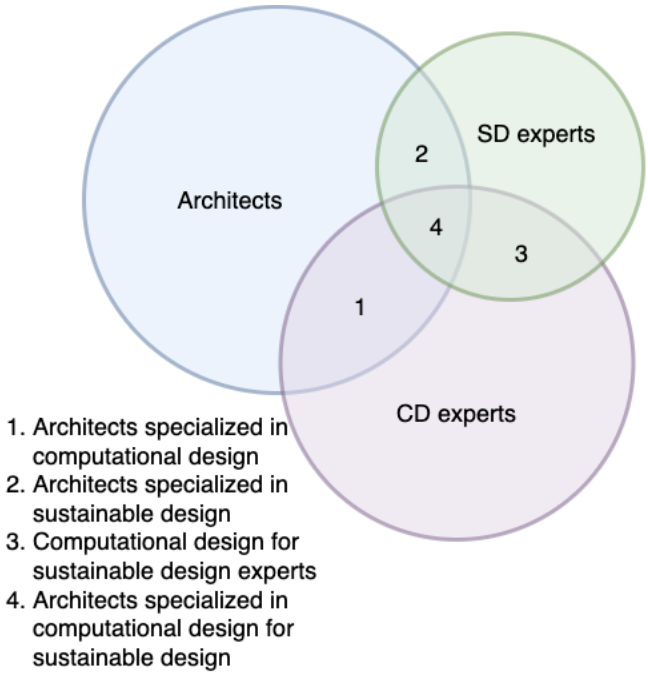

Figure 48 : Potential roles in SGD

Using the diagram in Figure 4 made in the state of the art (section 2.2.1), we have mapped the different roles of SGD according to the results obtained from the interviews. The actual roles encountered in SGD are mostly represented by the overlap 1 in Figure 48, with an exception at BSolutions, as mentioned in section 0, where architects and engineers with an expertise in sustainable design participate in the design through collaboration processes, represented in Figure 48 by overlap 2 and "SD experts". It can be surprising since sustainable design being a complex topic, an expertise is needed to assess the environmental factors correctly. We can also notice that no role mentioned were corresponding to the overlaps 3 and 4, confirming the lack of establishment of computational design for sustainable design in practices.

5.1.4 Conclusion: establishment of SGD in practices

In the methodology, we made the hypothesis that SGD wasn't established in practices due to the lack of literature on the subject. It has been confirmed by the results obtained from the interviews: when computational design is being used for sustainable design, it is mostly used through parametric design instead of generative design. The practice of SGD is scattered, thus difficult to generalize. Though, we have mapped in Table 26 below the characteristics of the practice in the offices of the interviewees, which can be used for further thesis as basis:

	SGD establishment in practices	Comments
Computational design type	Parametric Generative	The use of generative design for sustainable design is not yet established in practices, and when it’s the case, it is in the early stages of the adoption.
Design stages	Tender Later design stages	The use in later design stages is mostly due to the high level of detail required by LCA.
Parts of the project	Specific to each project	It can either be focused on façades, roofs or assess the whole geometry of the project.
Main objectives	Solar analysis Daylight analysis Wind analysis LCA	LCA is performed by all the offices, while solar is assessed in two offices and daylight and wind analyses are performed only at Grimshaw.
Toolsets	Rhino + Grasshopper Revit + Dynamo Ladybug One click LCA Totem	Totem is used in Belgian offices only, while One click LCA is used at Grimshaw.
Optimization	Optimization of the project	Single criteria optimization process
Roles	**Integrated** Computational design specialists BIM specialists Sustainability experts	There’s no dedicated role for SGD, and not even to generative design.

Table 26 : SGD establishment in practices - summary table

5.2 What are the barriers and drivers to SGD adoption?

During the interviews, we have collected data about the barriers and drivers to SGD adoption, as summarized in the Table 27 below:

Count of interviewees rmentioning the characteristic	1	2	3
Barriers	- Limited interoperability - Difficulty to quantify the results - Definition of the parameters - Cost - SD adoption - Different software per assessment type	- Limitative tools - Lack of time	- Skills required to use the tools - Skills required to understand the tools
Drivers	- Helps taking decisions - Generation of unpredicted shapes	- Time saving - Enhancing sustainability in projects	-

Table 27 : Barriers and drivers to SGD adoption - summary table

The characteristics mentioned by the interviewees are sorted according to the count of interviewees mentioning them, to have an overview of their importance. We can see that most of the barriers are only mentioned once, while the number of the barriers mentioned decrease based on the count of interviewees. It can mean that some barriers may come from a personal point of view rather than an objective one, but the limited number of interviewees prevent us from drawing conclusions in this regard.

In this section, since we already summarized the barriers and drivers in section 4.1.2.4, we will compare the barriers and drivers mentioned during the interviews to the characteristics of Spacemaker, to see if it suits the use of SGD in practice.

5.2.1 Barriers

The two most recurring barriers, mentioned by all the interviewees, are the **skills required to use and understand SGD tools**. We can note that Spacemaker can lower these barriers, and also the **lack of time** in order to learn these skills, mentioned twice during the interviews.

Regarding the **limitative tools**, the interviewees mentioned it as limitative for either **collaboration**, the **shape grammar** they offer and the **parameters that can modify the shape**. Concerning collaboration, Spacemaker can't be considered limitative since its platform is easy to use, fast to learn and let different team members work on the same project, in the same computational environment. As for the latter characteristics, we can state that Spacemaker is limitative in the shape grammar it proposes and the parameters it proposes to generate shapes. Indeed, the building shapes are limited to extruded volumes, and the drawing tools only allows bar-shaped buildings. As for the parameters to generate the volumes, we can only choose between 12 building layouts with small variations, and optimize the height of the buildings according to one chosen parameter between solar hours, daylight (OA) and VSC.

Concerning the barriers mentioned by only one interviewee, such as **limited interoperability** to begin with, we can state that it is the case for Spacemaker. Indeed, even if it allows import and export of geometries and information, such as geometries in IFC format, as mentioned in section 4.2.1.1, the geometries supported are very limited, since it allows only extruded surfaces to be imported. Furthermore, import and export through third party format is required.

As for the **difficulty to quantify the results and define the parameters** in order to generate the shape, since Spacemaker doesn't require coding skills the problem doesn't occur in this case. However, even though it facilitates the handling of the parameters and the form generation, the user is much more limited in the parameters, geometries and results that can be done than with a visual programming tool such as Grasshopper (Rutten, 2007).

Regarding the **cost** mentioned by A. Maes, Spacemaker's cost can create a barrier to the adoption of SGD. Indeed, with an annual subscribing of 4.635 € (Haukeland, 2019), several potential users will not be able to pay such a fee.

As for the **adoption of sustainable design**, it is up to the stakeholders to develop their skills. Such a tool can only, at best, make architects aware of the challenges of sustainable design.

Concerning the fact that **the software are usually focused on one assessment type**, Spacemaker provides a wide range of assessments, which are suitable in the early stages of the design as discussed in section 4.2.1.2, thus lowering also this barrier.

5.2.2 Drivers

About the drivers for the establishment of SGD in practices, such as the fact that it can be **time saving**, we can state that Spacemaker can have this advantage. Indeed, the fact that it is easy and fast to learn and **help in the decision process** enables the users to save time in the early stages of the design. It also helps to take into account sustainability during the early stages of the design, helping the designers **enhancing sustainability** during the design process. Regarding the **generation of unpredicted shapes**, since Spacemaker has a very limited shape grammar, it is unlikely to produce unpredicted shapes, even though some generated building layouts can be more efficient than the ones drawn by the users.

5.2.3 Conclusion: Barriers and drivers to SGD adoption in offices

In the section above, we have seen that there's actually more barriers than drivers to SGD adoption in offices, with actually the skills required to perform these kind of analyses and understand them as the main barriers, mentioned by all the three interviewees. A tool such as Spacemaker, which is meant to be easy to use and understand, helps lowering these barriers. It also helps lowering other barriers, such as the time needed to learn and use the tools, the limitation of collaboration, the difficulty to define parameters and quantify the results and the fact that usually, such software are specialized in one type of assessments. However, some barriers remain with Spacemaker, such as the limited shape grammar, the limited number of parameters to modify the shape, the limited interoperability, the cost and the adoption of sustainable design. In the next sections, we will assess whether Spacemaker is indeed suited for SGD.

5.3 Is a tool like Spacemaker responding to a need in the practice of SGD?

To answer this question, we assessed Spacemaker by comparing it to a computational framework found in literature, and to the needs mentioned in the interviews. Then, we can compare the needs of both academic research and practice, and see whether Spacemaker is corresponding to these needs or not.

5.3.1 Academic practice

At first, we will compare Spacemaker to a computational framework to assess sustainability found in literature.

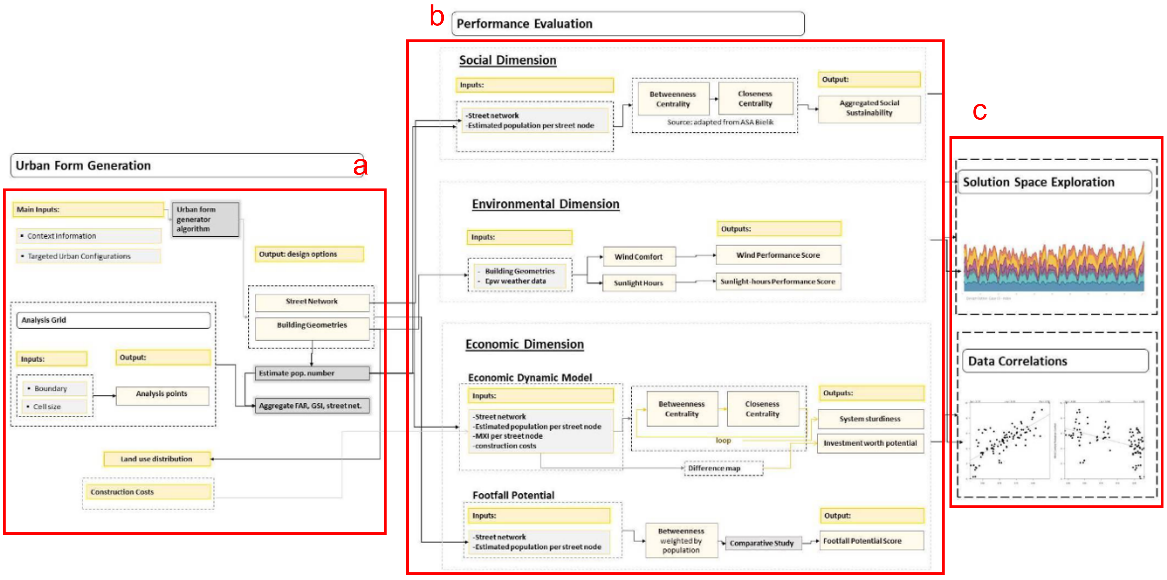

Figure 49 : Architecture of the framework (Elshani, et al., 2021)

The framework (Figure 49) is divided in three steps: First, the generation of the urban form using generative design method (Figure 49a), then, Elshani, et al. (2021) evaluate the generated propositions according to performance criteria (Figure 49b), and after that choose the best solution by summing up the performance of the proposition in each criterion (Figure 49c).

To generate the urban form, some specific input parameters have been put in place. This model uses street network orientation and density indicators as input parameters. The algorithm that generates the different design options uses therefore the street network orientation, and the Ground Space Index (GSI) and Floor Area Ratio (FAR) as density indicators.

Spacemaker however does not generate street networks, but the user is able to draw the streets manually. As for density factors, Spacemaker provides figures such as Building coverage and Gross Floor Area (Section 4.2.1.2). We can notice that neither GSI or FAR indicators are computed.

The evaluation of the performance, according to Elshani, et al. (2021), is divided into three sections, called by the authors "*the three pillars of sustainability*": Social, environmental and economical sustainability. The study focuses only on evaluation metrics that highly depends on urban form.

5.3.1.1 Social sustainability

Elshani, et al. (2021) mentions that *"an essential factor of equality that depends on the built environment is equal access".* In this workflow, they measure the accessibility of "*every individual*" to the "*lively spots*", which are part of the city with high interaction potential and high connectivity properties. In order to do this, the authors based their approach on a method developed by Bielik, et al. (2018) and estimates the population number based on the building geometries and uses it as a weight in the betweenness centrality calculation.

Here, we can see that Spacemaker does not provide such information. It can be justified by the fact that Spacemaker is made to work on a site scale to a district scale, while this method is more relevant in urban planning at a large scale.

5.3.1.2 Environmental sustainability

This framework is mostly based on sunlight hours and wind comfort performance, since they are the only microclimate analysis parameters that depend highly on the urban form (Reiter, 2010).
To assess wind comfort, Elshani, et al. (2021) are basing their algorithm on Lawson Wind Comfort Criteria, using computational fluid dynamics (CFD) for their calculations. They divide the different criteria into two categories: 1- the safe wind speed, where the area is considered comfortable for pedestrians and 2- the dangerous wind speed. They use the percentage of safe regions as an indicator for the performance of the urban form.

Considering the sunlight hours, Elshani, et al. (2021) are using the machine learning models of Infrared. To separate the vulnerable spots from the performing ones, they defined the threshold to 5,5 hours of sunlight, and consider the areas exposed to less than 5,5 hours vulnerable.

Spacemaker also assesses wind speed using also CFD, and assessing comfort with the Lawson Wind Comfort Criteria too, but offering the user the possibility to choose between different comfort scales. Another difference is that Spacemaker provides data sorted in five categories: sitting, standing, strolling, walking and uncomfortable wind speeds, allowing the user to have a more precise feedback. When looking at the sun analysis provided by Spacemaker, it is similar to the model used by Elshani, et al. (2021) by the fact that it assesses sunlit hours on ground and buildings surfaces, offering to the user the possibility to choose its own threshold, and see directly which parts of the project are problematic or not.

It can be surprising that the framework doesn't mention daylighting, since it has been recognized as a potential sustainable design strategy for buildings (Li & Wong, 2007), while Spacemaker provides these kind of analyses.

5.3.1.3 Economical sustainability

Using a model established by Bielik et al. (2019), Spacematrix method and Mixed-use index (MXI) method, which are special analysis methods that provide the measuring of land-use diversity and the density of built-mass (Ye & Van Nes, 2014); Elshani, et al. (2021) have two output performance indicators: the worth investment potential and the system sturdiness. Besides the dynamic model, they also use the footfall potential indicator as a proxy to choose locations with high economic potential.

As for Social sustainability, Spacemaker does not provide such performance indicators, but such indicators, like Spacematrix and MXI, can't be used at a district scale, since MXI quantifies the land-use mixture and measures the functional mix, based on the percentages of GFA of dwellings, working spaces and commercial amenities; and Spacematrix measures the building density and building types (Ye & Van Nes, 2014).

5.3.1.4 Is Spacemaker suited for the framework established by Elshani, et al.?

We have seen in the sections above that neither social sustainability and economical sustainability are covered by Spacemaker's analyses. However, the analyses related to environmental sustainability where at least as performing as the ones used by the authors. Spacemaker provided more detailed information regarding the different criteria, such as showing different categories for wind comfort and allowing the user to fix his own threshold for the sunlight hours. It also uses CFD, where its use is validated to assess the wind effects for pedestrian comfort (Reiter, 2010). Furthermore, Spacemaker provided other analyses regarding microclimate, such as temperature percentile, comfort frequency and daylight analysis (Section 4.2.1.2). It also analyzes the potential for photovoltaic energy production, which is also related to the sunlight analysis. In the Table 28 below, we can have an overview of the analyses provided by the framework and the ones provided by Spacemaker:

Analyses	Framework	Spacemaker	Comments
Social	- Accessibility	-	Difference of scales between Spacemaker and the framework
Environmental	- Sunlight hours - Wind comfort	- Sunlight hours - Wind comfort - Wind speed - Temperature percentile - Comfort frequency - Daylight analyses (VSC and OA)	The analyses provided by Spacemaker are also more precise, since it displays a broader range of information and the user can fix his own threshold.

Economical	- Worth investment potential - System sturdiness	-	The methods used in the framework can't be applied at the district scale.

Table 28 : Comparison of the chosen framework (Elshani, et al., 2021) with Spacemaker

It can also be noted that Spacemaker employs a similar workflow than the one established by Elshani, et al. (2021), as can be seen in Figure 50: at first, the propositions of the urban form are drawn, either manually or generated by the platform. Then, the propositions can be evaluated with different analyses, and the user can choose which solution suits him most with the help of a comparison tab (Figure 20). Then, the propositions are compared to each other, which is similar to the "data analysis" step in the workflow of the framework. We can also note that Spacemaker allows the user to optimize his project according to a chosen criterion, which can be sunlight hours, or daylight analysis (VSC or obstruction angle). The users can also modify their proposals at any time, which makes the process iterative; compared to a linear process in the chosen framework by Elshani et al. (2021), even though generative design is used to generate urban forms in the first step, which can be misleading regarding the process.

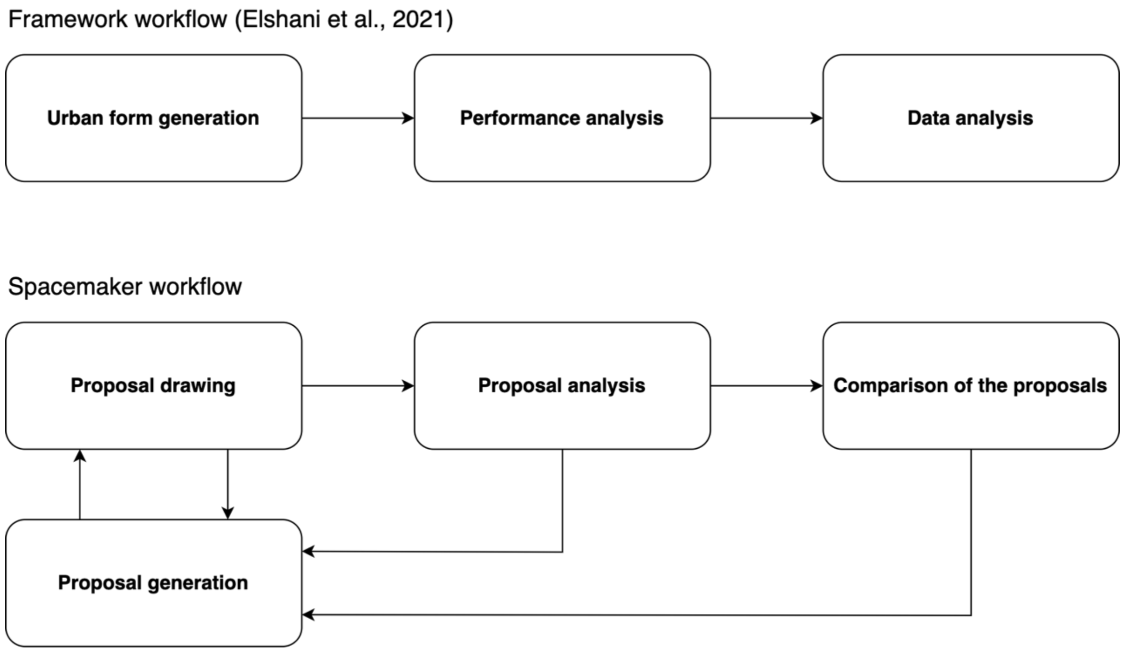

Figure 50 : Comparison of the workflow of the framework and a potential workflow in Spacemaker

We can conclude that even though Spacemaker isn't suited for social and economic sustainability, it is well suited to assess environmental sustainability through this kind of workflow. The fact that it assesses 13 types of analyses, instead of 2 in the case of the chosen reference, makes it more reliable, even though some analyses are still under development, like for instance microclimate analysis. Spacemaker is also more precise as it offers a broader range of values for each analysis (section 4.2.1.2). We can also take into account the fact that

Spacemaker is still under active development, meaning that we can expect more reliable analyses in a close future.

5.3.2 Comparison of Spacemaker with the offices needs

In the previous section (4.1.2.5), we identified several expected characteristics of sustainable generative design tools as follows:

Sustainable generative design tool			
Count of interviewees requiring the characteristic	**1**	**2**	**3**
Desired characteristics	- Collaborative - Fast analyses - Targeting the analyses - Assessments running in the background - Large shape grammar - Generation of information	- Easy to use - Easy to understand - Seamless interoperability	-

Table 29 : Summary of the desired characteristics of the ideal SGD tool - per number of interviewees that mention each characteristic

In this section, we will compare the actual characteristics of Spacemaker to the features mentioned by the interviewees, summarized in the Table 29 above. In this table, each characteristic is associated to a number of interviewees that mention it. We can notice that there's no characteristic mentioned by all the three interviewees, and only 3 features have been stated by two interviewees, meaning that we there's no consensus yet on the ideal tool for sustainable generative design. The limited number of interviewees means that we cannot generalize the information collected.

To begin with the **accessibility** of Spacemaker, the platform is made to be accessible to every architect, no matter what digital skills they have, as said on its website (Haukeland, 2019). It doesn't require coding or even visual programming skills to be used. Furthermore, the platform is entirely run from a web browser, making the accessibility easier regardless of the user's computer and operating system.

The **understanding** of the analyses results can be trickier, since it seems easy to understand with the graphics displayed directly on the 3D site and buildings. But such understanding is only possible with a knowledge of sustainability and of how the platform computes its analyses, to understand if the results are plausible and how to change the project accordingly.

Regarding the **interoperability** of the platform, it allows the import and export of data and geometries in a very basic level. Spacemaker's interoperability can't be called "seamless" as A. Maes was describing his need, since the model isn't updating itself automatically from a platform to the other. Extra steps of import/export through third party format are needed as have been already noted.

As for **collaboration**, the platform allows different users to work on the same project, either in a viewer, editor or admin role. Since Spacemaker is made such as the users don't need to know how to code or use visual programming, and works directly in a web browser, its accessibility doesn't weaken collaboration such as Ch. Dautremont was pointing out. The only barrier to collaboration is the handling of the tool itself, but since it can be learned within a few hours there wouldn't be huge gaps between the skills of the different stakeholders.

Concerning the analysis performed, we can say that the **calculation time** which was at a maximum of 30 min for wind assessments, is quite short, even though the calculation time depends on the size of the site. Most of the analyses would take up to 15 mins to be computed and displayed, and the user is allowed to run multiple analyses at a time. Furthermore, the generation of the buildings and the "manual" drawing were fast, and the whole assessment of the tool, which consisted of setting up a project, generating buildings and running analyses only took a few hours, as can be seen in the recordings. In order to save some time, the user can also **target the analyses** to run, which completes another criterion.

About the **assessments made in the background** mentioned by A. Watts, to describe an entirely passive process where architects wouldn't have to even use the program; we can state that Spacemaker may be suited for this kind of use. Indeed, the fact that the platform is made to be collaborative, and offers different roles and authorizations to the users, lets the team members organize the work so that some users only have access to the results of the analyses. Thus, the process can be passive for certain team members, in the case where a manager would generate the geometries, run the analyses and update the project, although it can't be automated yet.

The **shape grammar** of Spacemaker is currently limited to bars and towers, even though 12 layouts with small variations are proposed (Figure 18), such as an offset between buildings, or angular buildings. Finally, Spacemaker doesn't let the user **generate information** in the geometry such as stated by A. Maes; where each geometry would have information stored such as its story number or its function.

Count of interviewees requiring the characteristic	Desired characteristics	Spacemaker	Comments
1	- Collaborative - Fast analyses - Targeting the analyses - Assessments running in the background - Large shape grammar - Generation of information	- Collaborative - Fast analyses - Targeting the analyses - Assessments run by a manager - Limited shape grammar - None generation of information	The assessments can't be totally passive since it has to be undertaken by at least one stakeholder, but it can be a passive process for the other members of the team.
2	- Easy to use - Easy to understand - Seamless interoperability	- Easy to use - Easy to understand - Interoperability	The platform is intuitive but in order to properly understand the results, a knowledge of sustainability is still required. The interoperability cannot be called seamless since import/export through third party format is needed.

Table 30 : Comparison of Spacemaker with the desired characteristics of the interviewees

As we can see on the Table 30 above, Spacemaker corresponds to most of the desired characteristics mentioned by the interviewees. Indeed, all the three characteristics mentioned twice by the interviewees are met, with only the seamless interoperability which is not entirely met. As for the other characteristics, 4 out of 6 are met, with only the assessments run in the background which is not entirely met either.

As a conclusion, we can say that Spacemaker meets most of the desired characteristics mentioned by the interviewees, even though some of the needs are not met exactly as they are mentioned. Its main weakness is the very limited shape grammar, but the fact that solutions can be found for the assessments running in the background, and the interoperability of the platform makes Spacemaker fit for the needs mentioned.

5.3.3 Conclusion: Spacemaker compared to academic practice and office practice

When comparing Spacemaker to the hypothesis made during the methodology in section 3.4.2, even though Spacemaker targets non-experts, it meets most of the desired characteristics mentioned by the interviewees, as can be seen in Table 30 above. As for the reliability of the analyses proposed, even though most analyses rely on sound data and methods, like wind analyses for instance; some analyses like microclimate must be taken into account with more caution. This is mostly due to the lack of detailed information in the project, such as the building materials and the ground type, which has a significant impact the ground temperature. Though, these analyses must be taken into account as indicators to prevent issues in the project, not as detailed assessments. However, Spacemaker corresponds well to the needs mentioned by the interviewees, and to the framework chosen in literature.

To give a more personal opinion, the platform was very intuitive to use, and the website was well-documented to help us understand how the analyses are performed. The analyses were well-explained, and the results were displayed in the platform in a way that was easy to understand. Spacemaker's biggest flaw, according to us, is the very limited shape vocabulary, and the fact that simple extrusions do not take into account the irregularities in façades, such as balconies, or even materials, which can have an impact in solar, daylight analyses and microclimate analyses. Thus, Spacemaker is more suited for **early stage urban planning** than architectural design due to this lack of detailing in geometries.

5.4 Limitations of the thesis

As promising as the results appear, one must be cautious with their interpretation. Indeed, this thesis could be improved in several ways:

At first, the **number of interviewees** is very limited. It is mostly due to the short time period when the interviews have been conducted, and therefore more experts could have been interviewed to have more reliable data, especially with more **sustainability experts** to have balanced results.

The fact that the tools are chosen based on the **information gathered on their website** makes the choice of Spacemaker less reliable. To have a better overview, a test of the different platform would have been better, but due to the lack of time, it has not been done.

Concerning the **framework** chosen to compare Spacemaker, it doesn't give much specifications about the calculations for the assessments and the way that generative design is used. Thus, it is useful to give sustainability-oriented results, but to have a complete overview we need a generative design-oriented framework to compare Spacemaker. Comparison with multiple frameworks would have made more relevant results. It also makes the thesis **sustainability-oriented,** as well as the toolset overview that assess mostly the types of analyses instead of the generative design aspects.

To conduct the assessment of Spacemaker, it would have been more relevant to **compare the analyses and features** of the platform to other platform's analyses, such as Grasshopper alongside Ladybug tools, which is much more established thus making a good reference tool. It would also be useful to assess the features of the platform in **more detail**, and in a **generative design-oriented way**.

6 Conclusion

Sustainability in architecture is a complex objective with multiple criteria to address and optimize. By using generative design for sustainable architectural design, since it lets the users do performance-based design in a short amount of time, it has a great potential providing solutions and giving an overall feedback on the performances of the design. While usual generative design tools still require computer science skills, and thus create a barrier to the use of generative design, a new kind of platform is emerging, targeting non-specialists. These toolsets present a great potential in addressing these issues, and this thesis assesses the potentialities of these platforms in what we call *sustainable generative design*.

This work is divided in two parts: the first one is theoretical, and will serve as a basis for the second part, which is practical.

In the first part, we realized a literature review to define the different concepts, such as computational, generative, algorithmic design and sustainable generative design. Then, we assessed how SGD was used in literature, by assessing the roles and skills associated to SGD, and criteria such as the sustainability criteria assessed using SGD. We assessed the tools used in order to do SGD, such as visual programming tools, and generative design platforms.

The second part of the thesis is organized around three research questions:

1) How is SGD **established** in practice?
2) What are the **barriers and drivers** to SGD adoption?
3) Is a tool like Spacemaker responding to a **need** in the practice of SGD?

In order to answer these questions, we conducted interviews, completed by an assessment of one of the new emerging platforms, which is Spacemaker.

We began by assessing the establishment of SGD in offices, which was addressed by conducting interviews with computational and sustainable design experts. It confirmed our first hypothesis, which was that the establishment of SGD was scattered and not business as usual in offices. Indeed, as we expected, the practice of SGD has no dedicated role, and it is used only to solve very specific issues in a few projects that require it.

In order to understand why SGD was established or not in offices, we assessed the barriers and drivers to the adoption of SGD during the interviews. Unsurprisingly, the main barrier identified was the skills required in order to use and understand SGD tools. Other barriers, such as the time required to learn and use the tools, and the fact that the tools can also be limitative, have also been mentioned. In this section, we discussed the fact that the tool we assessed, Spacemaker, responded to some of the barriers and drivers, especially the skillset barriers. These positives results have been partially responding to the third question, which assessed whether Spacemaker was responding to a need in the practice of SGD.

The third question was not only answered by the results of the previous question, regarding the barriers and drivers, but also by comparing the results of the assessment of Spacemaker with a chosen literature framework, and to the needs mentioned in the interviews. Regarding the literature framework by Elshani, et al. (2021), which was meant to benchmark the evaluation of sustainability in urban environments using generative design methods, the authors divided the performance indicators into *three pillars of sustainability*: Social, environmental and economic. We could see that even though Spacemaker wasn't suited for social and economic sustainability, it corresponded to the workflow of the framework regarding the environmental sustainability. As for the comparison with the characteristics of an ideal toolset mentioned during the interviews, it helped us highlight the fact that Spacemaker corresponds to most of the characteristics mentioned by the interviewees. It is reinforced by the fact that the platform corresponds also to the barriers and drivers mentioned earlier in the thesis. According to our study, although Spacemaker has a poor shape grammar, it is well suited for early stage urban design.

Finally, it seems important to us to emphasize some points that we have not or little addressed but that should be developed in future work. The fact that this study focuses mostly on the analysis types of Spacemaker, instead of assessing the analysis methods of the platform creates an opportunity for future work. Moreover, since this thesis is sustainability-oriented, future research could be conducted in a generative-design oriented way, by comparing Spacemaker to generative design frameworks for instance. Finally, in order to confirm the suitability of Spacemaker in offices, a pilot experiment could be conducted.

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Annex 1: Interview grid

The interview grid can be found in the file “Annex 4” attached to this document.

Annex 2: Interview recordings

The video recordings of the interviews can be found in the “annex 2” folder attached to this document.

Annex 3: interview transcript

The interview transcript can be found in the “Annex 3” file attached to this document.

Annex 4: Toolset table

Applications	Software	Grasshopper + Galapagos/Octopus				Testfit	Hypar**	Spacemaker	PRISM	Archistar
		Ladybug	Honeybee	Butterfly	Dragonfly					
Scale	Building	x	x	x	0	x	x	x	x	x
	Urban	x	0	/	x	x	/	x	x	x
Design stage	Early	x	0	0	x	x	x	x	x	x
	Mid	/	x	/	/	/	x	/	/	
	Later	0	x	x	/	0	0	0	0	0
Creation	Districts	0	0	0	x	x	/	x	x	x
	Buildings	0	0	0	x	x	x	x	x	x
Analysis	Area	0	0	0	0	x	/	xx	x	x
	Cost	0	0	0	0	x	/	0	0	x
	Building type	0	0	0	0	x	x	xxx	xxx	x
	Building height	0	0	0	0	x	x	x	x	x
	Topography	0	0	0	0	x	/	x	0	0
	Daylight	x	x	0	0	0	x	x	0	0
	Noise	0	0	0	0	0	/	x	0	0
	Shadow	xx	0	0	0	0	x	x	0	x
	Sun	xxx	x	0	0	0	x	x	0	x
	View	x	x	0	0	0	x	x	0	0
	Wind	0	0	x	0	0	/	x	0	x
	Energy use	0	xx	0	xxx	0	/	0	0	0
	Climate	x	0	0	x	0	/	0	0	0
	HVAC	0	x	x	0	0	/	0	0	0
	Energy potential of the site	x	0	0	x	0	/	0	0	0
	Thermal comfort	xx	x	x	0	0	/	x	0	0
Score		11	7	3	5	5	6	14	5	7
Analysis type	Advanced	/	x	x	/	0	0	0	0	0
	Fast	x	0	0	x	x	x	x	x	x
Community-supported		x	x	x	x	0	x	/	/	/
Flexibility*		x	x	x	x	/	x	0	/	x
Accessible to non-specialists		0	0	0	0	x	x	x	x	x

x = 1 - 2   xx = 3 - 5   xxx = 6+

*Flexibility : The ability of the user to make his own analysis through visual programming, or writing code in python

**Hypar's function library is made by its community. There's no exhaustive list of the existing functions on their website.

Annex 5: Corrected toolset table

Applications	Software	Grasshopper + Galapagos/Octopus				Testfit	Hypar**	Spacemaker	PRISM	Archistar
		Ladybug	Honeybee	Butterfly	Dragonfly					
Scale	Building	x	x	x	0	x	x	0	x	x
	Urban	x	0	/	x	x	/	x	x	x
Design stage	Early	x	0	0	x	x	x	x	x	x
	Mid	/	x	/	/	/	x	0	/	
	Later	0	x	x	/	0	0	0	0	0
Creation	Districts	0	0	0	x	x	/	x	x	x
	Buildings	0	0	0	x	x	x	x	x	x
Analysis	Area	0	0	0	0	x	/	xx	x	x
	Cost	0	0	0	0	x	/	0	0	x
	Building type	0	0	0	0	x	x	xxx	xxx	x
	Building height	0	0	0	0	x	x	x	x	x
	Topography	0	0	0	0	x	/	x	0	0
	Daylight	x	x	0	0	0	x	x	0	0
	Noise	0	0	0	0	0	/	x	0	0
	Shadow	xx	0	0	0	0	x	x	0	x
	Sun	xxx	x	0	0	0	x	x	0	x
	View	x	x	0	0	0	x	x	0	0
	Wind	0	0	x	0	0	/	x	0	x
	Energy use	0	xx	0	xxx	0	/	0	0	0
	Climate	x	0	0	x	0	/	0	0	0
	HVAC	0	x	x	0	0	/	0	0	0
	Energy potential of the site	x	0	0	x	0	/	x	0	0
	Thermal comfort	xx	x	x	0	0	/	x	0	0
Score		11	7	3	5	5	6	15	5	7
Analysis type	Advanced	/	x	x	/	0	0	0	0	0
	Fast	x	0	0	x	x	x	x	x	x
Community-supported		x	x	x	x	0	x	/	/	/
Flexibility*		x	x	x	x	/	x	0	/	x
Accessible to non-specialists		0	0	0	0	x	x	x	x	x

x = 1 - 2 xx = 3 - 5 xxx = 6+

*Flexibility : The ability of the user to make his own analysis through visual programming, or writing code in python

**Hypar's function library is made by its community. There's no exhaustive list of the existing functions on their website.

Annex 6: Spacemaker exploration recordings

The recordings of the exploration of Spacemaker can be found in the “Annex 6” folder attached to this document.