Parametric modeling tools in small architectural offices: Towards an adapted design process model

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The transformation of architectural design practices has been underway for almost forty years, given the development and democratization of computer technology. Since then, architects have been continuously confronted with digital challenges; among those, the implementation of parametric modeling tools. While those challenges have been studied in the context of large companies, very few studies have focused on strategies and practices developed by small offices, even though they represent the largest part of the European market. In this underexplored context, researching the practice of five architectural firms lead us to reconsider and complete the typology of design process models developed by Blessing (1995), and to suggest a design process model mirroring how parametric modeling tools re-shape the design processes in small architectural offices.

Keywords: design models, design tools, digital design, parametric design, SME

Architects are permanently facing challenges related to the intertwined and complex nature of design projects, especially with regard to the increasing amount of information they need to integrate from the very beginning of the process. In response to these challenges, new and more powerful tools are constantly being developed and offered to them, amplifying a technological wave that sometimes stimulates them, sometimes overwhelms them, depending essentially on their digital culture and the context (socio-economic, structural, organizational) in which they operate on a daily basis (Bourbonnais, 2014).

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Computer Aided Drafting tools and Computer Aided Design tools currently on the market are efficient but do not satisfy, or no longer satisfy, all architects (16,5% of them express dissatisfaction, according to a recent survey conducted by the authors (Authors, 2018)). Due to the variable nature of architectural

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design (Bukhari, 2011), architects seek a design process that promotes change. Some of them have therefore started to use very different types of tools, namely parametric modeling tools. These modeling tools offer the possibility to take into account numerous parameters and to generate variations. Once implemented, this process contrasts totally, by its nature and efficiency, with the static properties of more traditional modeling methods used to create an instantiated model (Gallas & Delfosse, 2015).

Witnessing this emergence, researchers have started investigating the impacts of parametric modeling tools on architectural design processes. They report that architects demonstrate a growing interest for these tools, considering the new perspectives they open up in terms of workflow (Harding et al., 2012; Yu et al., 2015), morphological diversity (Wortmann & Tuncer, 2017) or in mastering the constructability (Shelden, 2002) for instance.

However, as firstly witnessed by the authors through previous work (Authors, 2018) and more thoroughly researched in this contribution, a large part of these studies has been conducted with regard to stabilized practices that have been established for several years in large architectural offices of international renown. Others, on the other hand, have been conducted on experimental contexts including controlled design conditions (pedagogical for example), that appear sometimes remote from field realities. The vast majority of architects from so-called "smaller structures", however, struggled and are still struggling to cope with the fast digital transformation (Carpo, 2017). As such, the distinction between a small and a large architectural firm is often used but still has never been strictly defined with regard to the architectural field specificities, at least to our knowledge. The definition of the size of large firms may already vary from one continent to another. When it comes to small and medium-sized enterprises (SMEs), we will refer to some of the existing literature (Borson, 2013; Ramos, 2017; Snoonian Glenn, 2018), and consider in this paper that a SME is constituted of less than 10 employees, which also corresponds to 99% of the European market (Architects'Council of Europe, 2019) and 77.7% of the offices in Belgium, country of origin of the authors (Authors, 2018).

Considering parametric modeling tools, the attitudes of these SMEs' "everyday architects", with whom we identify, are yet slowly changing. These architects, depending on their ability to act, slowly become ready to explore how parametric modeling tools could contribute to the development of projects better adapted to their expectations and creativity (Riccobono & Pellitteri, 2014; Terzidis, 2004). However, the use of such tools in such specific contexts requires the development of situated strategies. In that regard, Picon already formulated the following observation almost ten years ago:

"What about, for example, the day-to-day consequences of digital tools in small and medium-sized agencies, where they seem to be less of a creative field than a powerful leverage for standardization in an already fragile profession?" (interview with Chabard, 2012, p.3, authors translation).

As it is demonstrated that parametric modeling tools have profoundly reshaped the practice of large architectural firms (de Boissieu, 2013), there is now a need to focus on the digital practices and situated strategies developed by architects working in smaller architectural firms, which are studied very rarely even though they constitute the largest community of the actors involved on a daily basis in architectural design in Europe (Architects' Council of Europe, 2019).

Moreover, it appears that current research addressing digital transition have mainly focused on the development of tools and not on the understanding of the adjustment strategies and the workflow adaptations necessitated when integrating such tools. Yet, the apprehensions that architects might express, which might restrain them during the adoption process, also possibly reshape the workflows and models underlining the early phases of their architectural design processes. The coexistence of these two scientific approaches is therefore essential if we aim to avoid the development of technologies not suitable to the day-to-day realities of architectural SME's, and therefore not sustainable on the long-run.

In this paper, we thus specifically focus on the emergence of situated practices and strategies in architectural SMEs, with regard to the use of parametric modeling tools based on visual programming interface. This focus on visual programming interface justifies itself with regard to the emerging practices actually observed on the field, as it appeared that our case studies are mainly based on the use of Grasshopper©, a plug-in of Rhinoceros© as well as Dynamo©, developed by Autodesk©.

The paper starts by summarizing how the design process and architectural workflow have been modeled through time, and how these theoretical models have evolved until the progressive implementation of parametric modeling tools in architectural practices. We then quickly review the characteristics of these types of tools, considering various existing discourses. Later on, we classify the sample used for each study researching the use of parametric modeling tools. Through this classification, we highlight the missing data when it comes to research conducted in offices of small size, which thus confirms the relevance of focusing the research on such structures. We then develop the methodology applied to conduct our field research. We finally go through the results and suggest a renewed model of the design process supported by parametric modeling tools, given the practices and situated strategies implemented in the observed offices.

1 The design process represented over time

This section examines the major contributions that have structured the theoretical study and modeling of design processes. We start by reviewing some of the main models suggested to represent the design process through time, in a variety of design fields. We then go further by explaining some models taking into consideration the specificities of the architectural field, and then the integration of the digital component.

1.1 Main models of the design process over time

Similarly to architecture, the design process is the cornerstone of many professional fields, such as engineering, industry, mechanics, or computer sciences for instance (Darses et al., 2001; Safin et al., 2007). Several models of the design process have thus emerged from various design-related disciplines; among them the seminal theories of *Problem-Solution* by Simon (1969) and *See-Transform-See* proposed by Schön (1984). The definition of design itself still evolves over time, depending on the specific considerations of each era and each field. It has thus successively been considered the solution of a complex and ill-defined problem (Simon, 1969); an inventive and creative process (Darses, 2004); a conceptual result issued from the articulation of knowledge (C−K theory by Hatchuel & Weil, 2009) or the construction of representations (Visser, 2006, 2009).

In 2004, Dubberly and his colleagues listed through various disciplines (such as architecture, industrial design, mechanical engineering, quality management and software development) no less than twenty-four linear models; thirty-two linear models incorporating iterative loops; three tree models; seven spiral models; eight circular models and twelve various models, each representing a design process (Dubberly, 2004). This variety of models echoes multiple points of view regarding the design process, and especially their evolution over time. Design can indeed be defined in a general way or, on the contrary, according to its own field of application, not to mention that it can be deployed differently by designers from the same field (Safin, 2011). That being said, some researchers identify a common core to the design activity from one field to another, including for instance the repeated stages structuring several design process models (Motte & Bjärnemo, 2004), the influence of various individual parameters (such as expertise, training, personality and abilities) on the analogical modes of reasoning (Bonnardel, 2000; Leclercq & Heylighen, 2002) or problem decomposition strategies (Akin, 2001).

This diversity of theoretical representations and models of the design process have been clearly summarized by Blessing (1995) in four families, namely the linear, cyclic, Archimedean screw and converging conical helical models. These four types (illustrated in Figure 1) reflect the schematic evolution of the multiple and successive representations of the design process, evolving

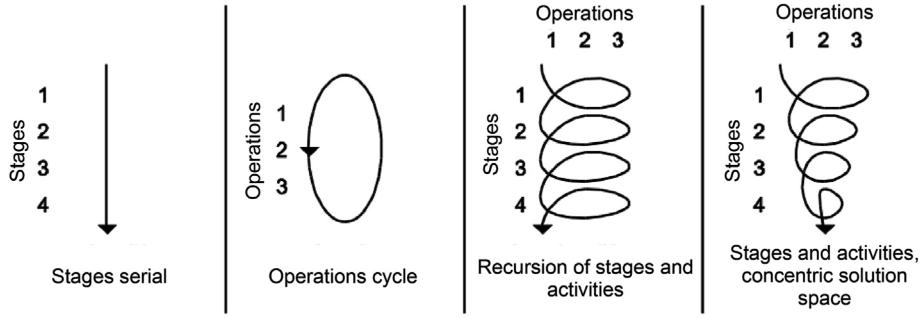

Figure 1 Typologies of design models by Blessing (1995)

from a basic linear scheme (analysis - synthesis - evaluation) into some more complex, multi-steps, iterative models.

1.2 Models illustrating the architectural design process: from the analog to the digital era

Looking now more specifically into each field as figured by the timeline below (Figure 2), we can distinguish models stemming from architectural design, from mechanical design or product design for example. Tom Markus (1969) and Tom Maver (1970) are among the first to have produced a map specific to the architectural design process. However, for some decades, the distinction between architectural design processes and engineering processes (notably) still nurtured lots of debates. In particular, Cross and Roozenburg (1992) modelled and compared the design process in engineering and architecture. In this research, these authors went back to the work of Hillier et al. (1984), looking at how these architectural design methodologists started to raise divergences between these two fields.

Later, Cross dedicated another book (2011) to clarify how designers think and work in various fields, including observations of architectural design processes. A few years later, specific models such as the System-enabler model by Ostwald (2012) and the Transparent layering system model by Chokhachian and Atun (2014) for instance more specifically integrated the specificities of architectural design. Among those specificities, one can highlight the diversity of constraints linked to the situated character of the artefact, the absence of prescribed methods, the diversity of the nature of representations, the need to represent the third dimension or the central role of the *parti* (Safin, 2011).

Beyond those field specificities, one has to observe that the design tools used to support such process, and especially during its early phases, have rarely been integrated into theoretical models, despite their growing importance (Abdelhameed, 2013; Schnabel, 2004). It thus became clear to researchers

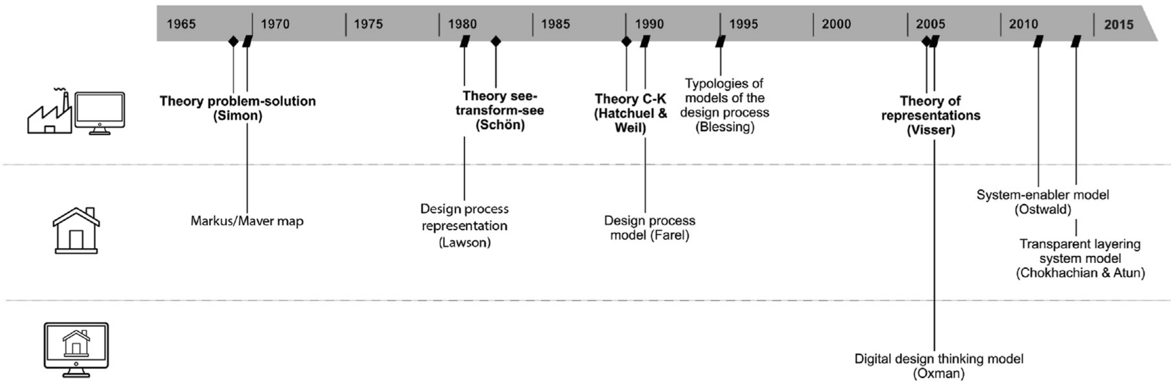

Figure 2 Timeline illustrating some of the main theories and models developed over time to support the fine-understanding of the design process. The specificities are studied for different domains, from top to bottom: all domains combined; in architecture; in digital architecture

that digital design and its increasing impact on design and production practices necessitated a re-examination of design theories, representations of workflows and models. A renewed conceptual framework and theoretical foundation for digital design itself were required.

Oxman was among the first ones to answer this call, suggesting the *digital design thinking model* (2006). This model is of particular interest because it clearly identifies the fact that the tools used during the design profoundly impact the design process itself. Indeed, although some concepts are common, the strategies and methods for exploring solutions may vary accordingly to the type of media used. Therefore, the nature of interactivity and the nature of control of the design process are both considered very important.

Since the implementation of parametric modeling tools in the architectural practice, many other theoretical propositions related to parametric modeling tools have been formulated, expanding our understanding of the workflows associated with such tools. One can relate to work conducted on the notion of Parametricism for instance (Schumacher, 2009), the study of specific skills required through parametric modeling (de Boissieu, 2013), or the approaches involved in the parametric design process (Hudson, 2010). Chokhachian and Atun (2014) pointed out the fact that parametric design specifically modified the relationship to the conceptual problem. They therefore suggested to bring the design stages closer to a more flexible system and to adopt and integrate different parameters and tools in the various design phases. However, by doing so these authors did not suggest a model to represent the design process *itself*, as supported or re-shaped by parametric modeling tools.

2 Parametric modeling tools based on existing discourses

This section is dedicated to understanding the functioning and framework induced by parametric modeling tools, based on previously published research. The first subsection shortly summarizes how the "parametric" concept emerged through time, and explains to what extent "Architettura Parametrica" roots into history of research and advanced practices. The second subsection rather discusses the characterization of the generic tool itself, the practices' changes documented with regard to these tools, and throughout the design process. The third subsection is an overview of the samples used in empirical and experimental studies, highlighting the value of focusing on architectural SME's.

2.1 Emergence of parametric modeling in architecture

Some theoretical foundations of parametric modeling as understood today, or at least of the "parametric logic" underlying our current understanding, can already be found in the work of Sullivan, Gaudi or Le Corbusier to name a few (Bottazzi, 2018). When it comes to the term itself, the concept and first use of the term 'Architettura Parametrica' are attributed to the architect Luigi Moretti in the 1940s, who initiated a discussion about the relationship between architectural design and parametric equations (Bucci & Mulazzani, 2002; Moretti, 1971).

Later, in the 70's, a new "digital design era" slowly emerged. Ivan Sutherland's work with Sketchpad pioneered a new generation of researchers trying to put software engineering potentials to work to the benefit of designers. Later, John Frazer (1995) and Paul Coates (2010) became leaders of emerging fields identified as "generative design" and "evolutionary computation".

These new paths of formal exploration thus enriched Moretti's concept of "parametric architecture", although our current understanding of the term remains fundamentally close to Moretti's description (Frazer, 2016). The next section clarifies more recent characterization of parametric modeling tools and delineates their inherent potentialities for design.

2.2 Characterization of parametric modeling tools

In parametric modeling tools, the model is generated and visualized through two types of interfaces. First, in line with a more traditional way to manipulate 3D objects, we find the graphical representation of the geometry of the model. This representation is then accompanied by a programming interface using algorithms specific to modelers and allowing the model to be recalculated when elements of either representation are modified (Agbodan, 2002). Thus, through the use of such parametric modeling tools, designers are required to model a conceptual structure that guides variations and that matches the 3D model of the artifact being designed (Aish & Woodbury, 2005; Kolarevic, 2005) (Figure 3). This approach requires the designer to invest time and effort in an intermediate stage between idea and design. In this stage, the designer produces the algorithmic description of the intended design (Leitão, 2013) including the logic and dependencies between input parameters, dependent geometric operations. The 3D model is then created by the execution of the algorithm. Therefore, the production of the algorithm actually precedes the generation of the shape. This major change in approaching the iterative design of a virtual artefact goes hand in hand with a fundamental cognitive shift, from modeling a designed "object" to modeling the "logic" of its design (Leach, 2009). If digital representation henceforth translates the process, we can consider that architects no longer design a building itself, but rather its process. This enables the architect to explore beyond the design ideas originally envisioned, in a way that would be impossible with traditional design and modeling approaches (Aish & Bredella, 2017).

One interesting notion peculiar to parametric modeling is described in Hernandez's work (2006, p.310): *"Parametric Design is the process of designing*

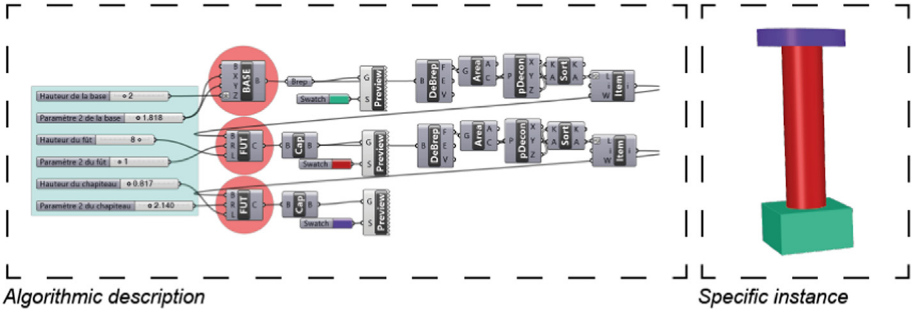

Figure 3 Algorithm developed through Grasshopper© and the related 3D representation of one of its possible instances. Picture by authors

in environment where design variations are effortless, thus replacing singularity with multiplicity in the design process." Through this design workflow, exploring through this "multiplicity of instances", the designer has the ability to generate different spatial and technical configurations starting from a single initial parametric model, just by editing the parameters. When the value of one parameter is changed, the modification is propagated through the chain of dependencies of the modified parameter, inducing other parameters to adapt automatically (Hernandez, 2006; Ostwald, 2012). The control of the parameters then makes it possible to create particular design instances from a potentially infinite range of possibilities (Kolarevic, 2005; Lawson, 2002; Oxman, 2017; Whitehead & Peters, 2008). As such, the possible evolution of design criteria makes parametric models particularly useful for extensive conceptual exploration.

While this process theoretically induces an almost-limitless adaptability of the model stemming from the reactivity of parametric modeling software, it has been yet reported that parametric modeling might also constrain in certain ways the design process (Aish & Woodbury, 2005; Harding et al., 2012; Harding & Shepherd, 2017; Iordanova et al., 2009). At some point, the complexity of the graph and its supposedly infinite possibilities do indeed reach their limits to remain understandable. The increasing complexity thus reduces at a certain level the flexibility and adaptability of the algorithmic description itself.

Such parametric modeling tools have recently permeated empirical and experimental architectural processes and have drawn attention of a growing number of researchers. The next section puts in perspective the milestones studies that slowly built up our understanding of what a parametric process might be, and how to characterize such a process.

Table 1 A look into research done about parametric practices

Authors and year	*Topic*	*Country of the research*	*Students*		*SMEs*		*Large offices*		*Offices with no specific size*	
			−	+	−	+	−	+	−	+
Shelden, 2002	Digital surface representation and the constructability of Gehry's Architecture	USA						x		
Aish & Woodbury, 2005	Identification of interactions during the parametric design process	Unspecified (country of authors: Canada)	Not indicated						Not indicated	
Dokonal & Knight, 2008	State of digital architectural design	UK, Austria	x		Not indicated					
Peters & Whitehead, 2008	Discussion on geometry, shape, complexity with an algorithmic approach	UK						x		
Iordanova et al., 2009	Evaluation of creativity related to parametrics	Canada	Not indicated							
Guidera, 2011	Conceptual design, exploration using parametric computing	USA	x							
Hudson et al., 2011	Identification of parametric benefits through a case study	USA						x		
Chien & Yeh, 2012	Creative design process in parametric design	Unspecified (country of authors: Taiwan)								x
Harding et al., 2012	Suggestions to think topologically at the early stage of a parametric design process	UK	Theoretical research without participant							
	Parametric modeling in architectural design: characterization of cognitive operations	France	x					x		
Yu et al., 2013	Comparing designers problem-solving behavior in a parametric design environment and a geometric modeling environment	Unspecified (country of authors: Australia)								x
Abdelmohsen & Massoud, 2015	Understanding the concepts of a complex morphology via computer	Egypt	Not indicated							
Gallas & Delfosse, 2015	Development of the Parametric puzzle method	France & Belgium	x							

(*continued on next page*)

Table 1 (*continued*)

Authors and year	*Topic*	*Country of the research*	*Students*		*SMEs*		*Large offices*		*Offices with no specific size*	
			−	+	−	+	−	+	−	+
Yu et al., 2015	Cognitive behaviour during parametric design	Not indicated								
Lee & Ostwald, 2016	Cognitive and linguistic approaches to parametrics	Australia							Not indicated	
Aish & Hanna, 2017	Comparison of parametric design systems for teaching design computation	UK	x							
Bhooshan, 2017	From research to parametric practice into projects of Zaha Hadid Architects Computation and Design group	UK						x		
Harding & Shepherd, 2017	Explanation of the Meta-Parametric Design approach	UK & Denmark							Not indicated	
Wortmann & Tuncer, 2017	Digital workflows in contemporary architecture	Out of purpose							Not indicated	
Yu et al., 2018	Comparing creativity in a parametric design environment and a geometric modeling environment	Unspecified (country of authors: Australia)								x

With regard to each column (i.e. each category of observed participants) the minus (−) and plus (+) indicate how familiar those participants are with the technology, according to the respective authors.The "Not indicated" annotation identifies a research field listed by the authors, but without any information about the participants' familiarity with the technology (Source: Authors).

Table 2 Synthesis of the case studies. The "available data" reflects how we were allowed to capture data once on the field

Method	*Retrospective interviews*				In situ *observations*	
References	*R1*	*R2*	*R3*	*A_C, A_L, A_X*	*D*	*A_FH, A_M*
Location	Liège	Brussels	Isnes	Brussels	Chaudfontaine	Brussels
Size	3 partners and 1 intern	6-person team incl. 2 partners, 4 architects	16 architects' team inside a larger contractor company of over 100 collaborators	16-person team incl. 4 partners, 12 architects	5-person team incl. 4 architects, 1 administrative	16-person team incl. 4 partners, 12 architects (same company as for the interviews)
Level of parametric expertise	Advanced	Expert	Advanced	Expert	Novice	Expert
Parametric modeler used	Grasshopper	Grasshopper	Dynamo	Grasshopper	Grasshopper	Grasshopper
Projects followed	2 projects: fire station, single-family house renovation	2 projects: headquarter, single-family house	Workflow in general	3 projects: massing for apartment buildings, hotel renovation, massing for mixed project (offices, retail, housing)	1 project: sport center	2 projects: hotel, mixed project (offices and housing)
Available data	Architect's discourse + physical traces + video recording	Architect's discourse + physical traces + pictures	Architect's discourse + physical traces	Architect's discourse + physical traces + video recording	Summary of meetings (written field notes)	Architect's discourse + video recording + founder's interview
Duration	56 min	65 min	62 min	40 min 25 min 1h40	2h30 + emails exchange	7h25 1h55

2.3 Context of the research projects conducted on parametric modeling

For a few years now, the literature tends to announce that parametric practice is (being) established in architectural offices (Harding et al., 2012; Yu et al., 2015; Yu et al., 2018). However, these studies rarely put forward figures quantifying and describing the state of actual practices (their maturity, the adoption processes) in architectural offices. The majority of studies are indeed carried out in experimental academic or in large architectural offices which do not reflect the practice of the majority of architects. On the contrary, a European survey studying the architectural profession in Europe in 2018 (Architects' Council of Europe, 2019) reveals that 99% of architectural offices are composed of less than ten people, and even 71% are composed of only one person. This survey also shows that the number of medium-sized offices is continuously decreasing in favour of even smaller structures.

While large architectural firms might have indeed internalized their own research and development teams, and have thus sometimes developed or adapted their own parametric modeling software (Bhooshan, 2017; Shelden, 2002), little is known about the strategies developed by small and medium architectural firms.

Following up existing literature on this topic, the only study paving the way on how small agencies deal with digital tools was initiated in Austria and England, but could not be fully carried out due to lack of architects' participation (Dokonal & Knight, 2008). Additionally, the aim of this research was to collect architects' opinions by means of questionnaires and not to observe their practices in the field.

Table 1 below thus summarizes the panels of previous research and highlights (in the grey column) the little interest for SMEs practices in general, and for the use of parametric tools in particular.

We therefore identify a gap of knowledge about the parametric practices of small architectural offices, yet representing the majority of architectural firms. We argue it is nowadays essential to collect data from practicing architects in such small offices, be they inexperienced, novices or experts in using parametric modeling tools. This research field will thus help to understand how the technology is integrated (or not) into the daily practice of 99% of the European architects, and what constraints they face when trying to settle in the use of parametric modeling tools.

3 Methodology

This paper documents parts of a larger research project that identifies the cognitive and organizational strategies and adaptations deployed for the integration of parametric tools into the architectural design processes of SMEs. Although a large-scale survey conducted during this research project points to the low development of parametric practices among small offices, at least in Belgium (Authors, 2018), its results also highlight the emergence of diversified practices among a small part of those SME's. It appears we are currently at a tipping point with regard to these emerging practices, that could either lead to large-scale adoption phenomenon or, on the other hand, to fast disengagement if the current parametric modeling tools appear unfitted to those "everyday" architects' down-to-earth constraints.

The next section starts by explaining the methods used in order to conduct the research presented in this paper and resumes the different case studies part of our data collection. We then summarize the precautions and tools put in place to lead the *in situ* observations.

3.1 Methods used for each case study

Given the complex nature of emergent digital practices, and given the intrinsically complex, situated, socio-materially distributed nature of any architectural practice (Le Dantec, 2010), we considered ethnographic, on-field inquiry as the most appropriate methodology to research the adoption of parametric modeling tools in architectural SME's (Yaneva, 2018; Yin, 2014).

We therefore deployed two methods to capture some of the diversity of parametric practices in SMEs (Table 2). First, we conducted *in situ* observations of two architecture firms using parametric modeling tools to develop different projects. In order to complete the data collected through the sole ethnographic approach, we resorted to capture data through a "think aloud" method during these *in situ* observations (as often as possible considering the architects' willingness to contribute that way), i.e. asking the designers to verbalize aloud any thought passing through his/her mind during the designing process. This data collection, although extremely tiring for the observed participant and although going beyond traditional data collection methods suggested by ethnographic inquiry, allows the researcher to understand in a rather fine-grained detail the unfolding cognitive process otherwise largely tacit, and thus difficult (or even impossible) to capture (van Someren et al., 1994). Additional precautions taken when implementing *in situ* observations are described in the following section.

When current projects did not allow for *in situ* observations, we analyzed agencies' practices through in-depth, semi-directive, retrospective interviews (i.e. structured around the *in situ* manipulation and analysis of traces of past projects, see Brinkmann, 2014 or Lallemand & Gronier, 2016). Those traces, collected by the interviewees themselves, could be of various nature (parametric files, sketches, diaries, …) and helped them reach as much retrospective accuracy as possible. The interviews' questions were structured around four main themes: the company (history, size, organization, …); their use of parametric modeling tools (familiarity, evolution, number of projects, difficulties, advantages, …); retrospective, narrative presentation of the selected projects (be they successfully implemented through parametric modeling tools or completely aborted) and open-ended questions about their expectations and critical thinking with regard to such tools. Interviews were audiotaped and later completely transcribed, using a simplified version of Jefferson's coding system (Jefferson, 2004).

Side-by-side with on-field observations, these in-depth interviews made it possible to grasp the parametric practices that could not be observed within the time frame of the research. Both methods offered complementary insights helping us understand the variety of emerging adoption strategies intertwined in the "designerly ways of knowing" (Cross, 1982). The data, although peculiar and extremely context-dependent, were extracted in an effort to initiate some mapping of a panorama of (sometimes overlapping, sometimes extremely diverse) situated practices, and *in fine* to nurture the drawing of an adapted design process model. The combination of these two methods somehow compensates for the limited quantity of analyzed projects, as the strengths of one method balance the weaknesses of the other (Leonard-Barton, 1990).

Given the low development of parametric practice in Belgian small architectural offices (Authors, 2018), we knew that the current scope of accessible fields would be limited and yet there was a crucial need to conduct research at this key moment. The case studies were thus selected following a two-steps process. First, we reviewed each of the 572 answers received with regard to a large-scale survey distributed at a previous stage of the research project (see Authors, 2018). Among those answers, some respondents expressed (through a final, open-ended question) interest and curiosity with regard to our research question and provided their contact info; the respondents also provided their self-defined levels of familiarity with parametric modeling tools. Secondly, starting from that existing database, we researched the companies' websites in order to better frame each team in terms of size, projects' types and scale and thus pre-selected a few of them, that would allow us to cover a broad range of SME's practices. After initial contact, among those only five expressed interest to participate in our research project and were eventually chosen as cases to study.

Retrospectively, after data collection and treatment, we can attest of those cases' relevance because of the diversity of appropriation of parametric modeling (in different offices or within the same one), at least with regard to french-speaking Belgian offices. Those cases thus allow us to report:

- the external use of parametric modeling: this is the case of the office [D] when subcontracting the modeling of the facades of a sports hall;
- the use of parametric modeling by an expert inside the design team per se, but disconnected from the design process: this is the case for the [A_FH] and [A_M] projects (an hotel; an office + housing project);
- the internal use of parametric modeling in support of the architectural design process; i.e. a parametric modeling being implemented by a designer also (partly) in charge of the design process by itself. This is the case for the design of the [A_C] project as well as the [A_L] project, and the [A_X] project for the development of a site plan.

The five cases, although naturally not conveying any universal, representative, positivistic "truth", nevertheless cover a rich range of practices, types of projects (from family housing to large-scale mass planing) and familiarities with the parametric modeling tools (novice, advanced, expert).

3.2 *Precautions and analysis grid for* in situ *observations*

As *in situ* observations can lead to some form of subjectivity, known under the Hawthorne effect (Roethlisberger & Dickson, 1939), two precautions have been taken: in terms of the researcher's posture and in terms of the selection criteria adopted to sort out the data collected. Based on the writings of Baker (2006), we opted for the full observer position in order to keep a distance from the observed action. Despite this complete observer's distance, the researcher remains immersed in the observed environment, which offers rich insights into the situated practices but can also lead to another form of subjectivity in terms of data acquisition, screening and analysis (McDonald, 2005). In order to select the data to be processed as objectively as possible, a triangulation was thus carried out by the co-authors who independently selected and then confronted what they considered to be key moments among the audio and video recordings. When agreeing on the selection of the key sequences, the experts relied on "*an already segmented social flow*" (de Sardan, 2008, p. 147) corresponding to changes in tools, tasks and reasoning in particular, that justify switching from one sequence to another. The experts then adjusted and completed the selection process thanks to their expertise, two of them carrying a background in architecture and one being an expert of parametric modeling.

While these recordings supported an a-posteriori analysis, an observation grid helped the observer (first author of this paper) to focus on a few key elements as the research field unfolded. The grid essentially contained four types of information. First, for descriptive purposes, the grid collected various information in order to reference and contextualize the observed moment (time, actors involved, pursued goal or raised question, …). Second, the grid helped to identify the tools used at each moment, with regard to the action in progress (sketch, references, digital tools, …). These actions were then identified through the spontaneous verbalization of the designer who externalized his thoughts, either to other colleagues or to the observer (following a spontaneous think-aloud process). In order to understand the dynamics between the tools and the actions carried out, the grid eventually helped us characterize the theme to which the action related. For all the cases studied, a complete transcript has been made (data available on demand).

The cases studied, which main results will be presented in the next section, were not selected for their "typical nature" or representativeness of a current architectural practice. On the contrary, those emerging practices figure alternative ways to approach and use parametric modeling tools, and as such rather position themselves on a panorama of adoption possibilities. In any case, our goal is not to define how architects *should* integrate parametric modeling tools at all costs. The objective of this research phase is rather to document current parametric practices in small architectural practices and to initiate some kind of "observatory of practices", nurturing situated, usage-driven reflections about those emerging practices.

4 *Observations resulting from a process-driven approach*

Although the world of architectural media has become more diverse, graphic and digital representations have in most cases continued to represent the artifact under the same representational paradigm, but through different tools (Derycke, 2012). Our results show that parametric modeling, however, modifies the content of the representation, or at least part of it, as well as when and how the architect relies on it. As mentioned above, parametric modeling indeed requires the designer to model not only the designed artifact, but also a conceptual structure that guides the design exploration, namely the algorithmic definition. Not only does this algorithmic definition constitute a fundamentally different way to articulate design input, but it forces the architects to explicit early on their design intentions with a high degree of accuracy before parametric exploration can begin (Dino, 2012). In that regard, one of the interviewed architects states: *"Well, the recurrences up to now were related to a fairly precise idea of what I wanted to model. So it's for sure. […] I never open a Grasshopper file and say: here, I'll see what it looks like with a couple of tricks."* [R1, author translation].

Another architect at that point intensifies the use of sketches in order to set up his reflexive process on paper and thus in order to define the constraints which are then transformed into parameters that frame the parametric modeling: *"We draw much more on paper in fact since we do a lot of sketches upstream and we also sketch on screenshots. So we draw things because it always takes time, especially because, when we work with curved surfaces, um, so sometimes*

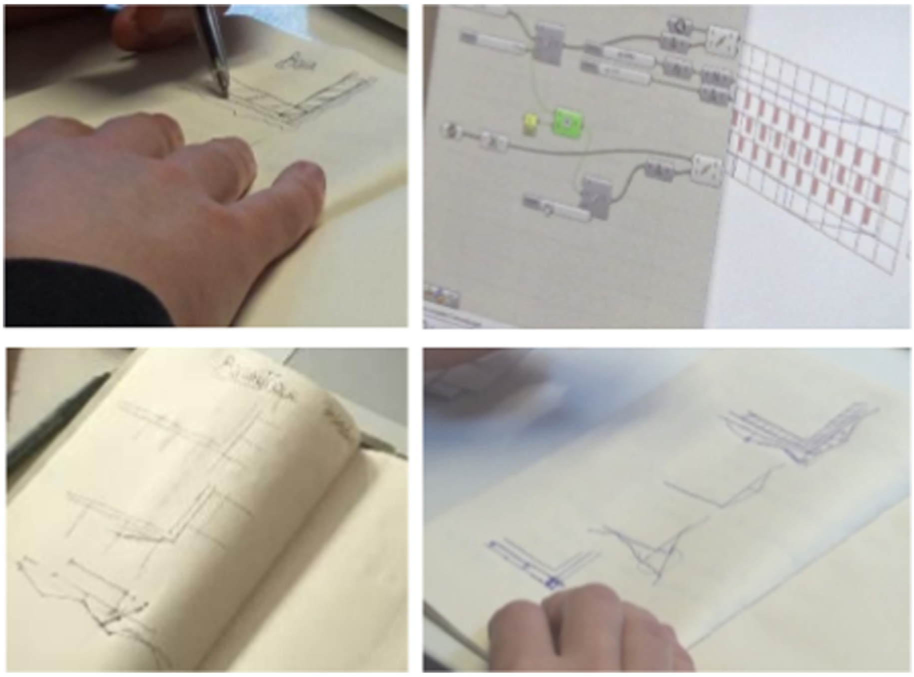

Figure 4 Illustrations of key moments on the A_FH project. The architect tries to find the appropriate algorithmic path to design the details of a facade. By doing so, and by testing a few variations through manipulation of parameters, he realizes how the design of the facade impacts the thickness of insulation, but also the way the panels from two contiguous facades connect to each other. The back and forth move between both design tools hence supports his thinking

we want to visualize faster, we sketch, and then if it's approved […] Or if it's good, we spend time modeling" [R2-96, 98].

Repeatedly, the interviewees address this need for a "reflexive step" found to be a fundamental notion arising from the use of parametric modeling. This reflexive process translates into some forced and early explicitation of the design intent, necessitated by the implementation of the algorithmic definition. We argue that this new form of intermediate representation, i.e. this renewed way for information to be presented and manipulated, effectively impacts the designer's thinking and pushes her/him to "think the process" rather than the final design. This cognitive shift has previously been noticed by Leach (2009), indicating a switch from object modeling to logic modeling.

This shift is also a lever for architects to promote their conceptual development, as one interviewee comments: *"And so, for example, when we did the competition, we focused not only on the results but also on the process. And how to help these questions, you know."* [A, author translation]. More than a mere *representation* support tool, parametric modeling can thus without a doubt be considered as a *design* support tool, as architects use it to support upstream design thinking. Going one step further, we even suggest that the use of parametric modeling tools initiate another form of design process, some "go and forth" iterative process between representation and design, as expressed by one of the interviewee: *"I was saying that this* [i.e. a parametric model] *was for visualization purposes, well, … when you vary the parameters, well for me, it comes back to design […] Even if the design gets more fixed with time. It's more like formal research. […] It becomes design somewhere."* [R1, author translation]. Similarly, through an experiment with expert designers, Yu et al. (2013) concluded that during the parametric design process, designers get inspiration from what they see on the screen; at the same time, they reflect on what they see and what they do by taking action through making rules. In Schön's view (1983), designers draw not only to communicate with others but to pursue a line of thought and to 'see' new possibilities or problems. More recently, Lawson (2005) has described designers using computers as having 'conversational' interactions with their computers about their designs. Therefore, we suggest that designers do enter some form of "see-transform-see" process when interacting with both their algorithmic definition and their parametric models, in addition to other "see-transform-see" reflexive processes that can occur in parallel on additional supports.

Indeed, our *in situ* observations revealed that architects do not exclusively rely on the parametric modeling interface when designing their artifact, as they are also constantly referring to other media (computer-generated images, sketches, verbalized thoughts) to support their thinking. This observed skill in the context of parametric modeling echoes Lawson's earlier observations (2005): "*It seems likely that a key skill for designers generally is not just the ability to make a variety of representations but to select them appropriately in order best to further understand the problems surrounding the current design solution state*" (p.294).

For one of the interviewees [A_FH], this concretely translates into a cognitive reflection upstream of the modeling but without any particular support. For another architect, it requires going back to free-hand sketching: "*my approach includes a sketch and a paper structure*." [R1, author translation]. This translation into hand sketches allows the first guidelines of the project to be put in place, which will then be mathematically translated to become constraints in the algorithmic definition. Thus, it seems that for those architects free-hand sketches still act as reflexive, external support to think about the designed artifact, but also to think about the design process, i.e. in this case the implementation of the algorithm and of the underlying logic that will instantiate into the final, selected variant. Through the observed cases, the algorithmic definition is thus constructed back and forth not only between the graphical and the visual representations offered by the interface, but also back and forth between other media, mostly sketching, such as illustrated below (Figure 4).

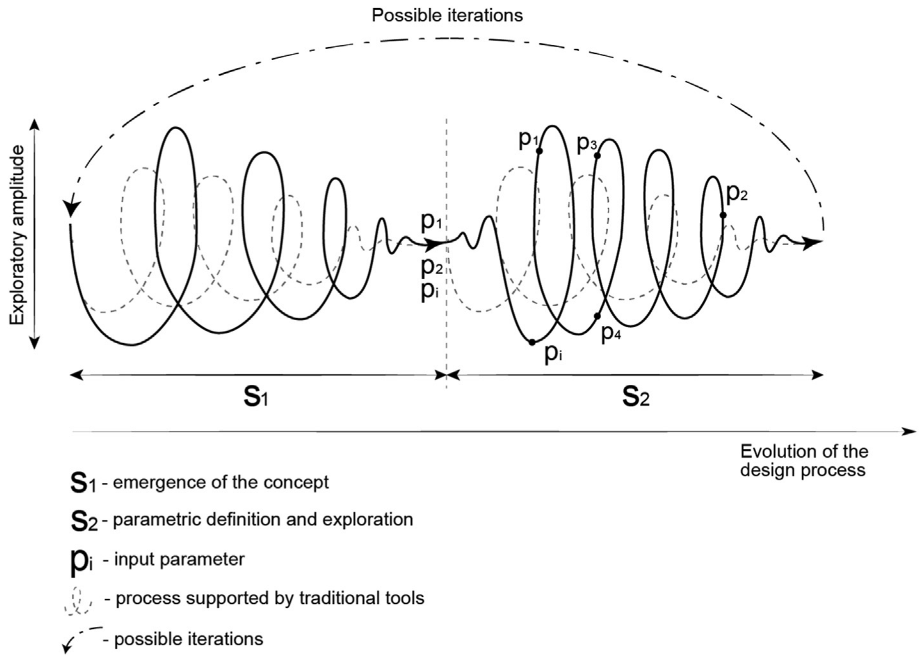

Figure 5 Design process model supported by parametric modeling tools (solid line), in comparison with design process model supported by "traditional tools" (dotted line)

Despite these back and forth movements with other design support tools, one has to acknowledge the fact that parametric modeling tools, and specifically this early and forced explicitation process, might constrain architects considering the limited number of various algorithms one can reasonably test in order to remain operational. Designers are forced to converge and consider in advance the changes that will have to be made during the process. As it has already been expressed through theoretical contributions and observed in various experimental contexts (other than SMEs, see Table 1: Aish & Woodbury, 2005; Harding et al., 2012; Davis, 2013; Harding & Shepherd, 2017; Iordanova et al., 2009), parametric modeling can be described as initially offering some limited exploratory zone that does not actually allow for unlimited conceptual variations, as suggested in theory.

Yet, knowing about this rather limited exploratory zone also encourages architects to think over the process twice and to anticipate how the project could be reshaped through the design process. One the interviewees comments: *"He* [the chief architect] *wanted us to be able to do* [curvy shapes] *..., the line here can do this, like a snake. So at first, he talked about curves, but I already knew that at the end it wouldn't be curved, so I had already planned a switch as shown by the yes-no button, so it was either curved or not curved."* [A_C_1, author translation].

If not correctly anticipated, the algorithm can in some way limit creative discovery if a major redesign of the model is necessary but impossible, due to lack of time for example. This phenomenon echoes the notion of *negative premature fixation* associated with many digital design tools (Dow et al., 2010), as well as with the notion of *circumscribed thinking*, i.e. when the designer is influenced by the limits of the tool, or at least by the limits imposed by his personal expertise with the tool (Robertson & Radcliffe, 2009), as one interviewed architect commented: *"Creativity […] is framed because you act within the limits of what you can do with the software."* [author translation].

At the same time, the number of iterations potentially explored in the time available thanks to parametric modeling tools increases the variety of design possibilities considered by architects. As one interviewee pointed out *"When you don't have parametrics, and even more in general when you don't have a few simulation tools like this that allow you to do iterations of fifteen seconds to one minute, you explore two or three cases. […] In any case, you don't have time to do more. So today we don't reduce the time, we keep the same time, we work neither less nor more, it's just you explore more"* [A, author translation]. This possibility for extensive exploration echoes the observations made by Iordanova et al. (2009) in a pedagogical experimental context, showing that designers' ideas are generated rapidly through parametric modeling, while new ones also simultaneously emerge as possible variations to be tested.

Parametric modeling thus requires to find a balance with regard to algorithm exploration and definition, with the help of other design support tools, and with regard to this iterative process, back-and-forth move between representation and design.

5 *A renewed design process model to integrate the impact of parametric modeling tools*

Some authors, including us, do not aim to formulate some new hypotheses explaining design phenomena but rather try to model the processes they observe in order to measure the impact of an identified factor, in our case the introduction of a new type of design tool. We underline again that the theoretical model we suggest here results from the observations that we conducted, revealing emergent appropriations schemes in some Belgian SMEs, and do not chase after some unrealistic, ideal theoretical use of parametric modeling tools. Considering how the relationship to the conceptual problem has evolved since the use of parametric modeling tools (Foster & Partners, 2006; Oxman & Oxman, 2014; Schnabel, 2012), we therefore suggest to adapt the theoretical model of the parametric design process, taking into account its specificities. First of all, after reviewing existing models of the design process, it seems necessary to go beyond the "one-by-one" integration of design support tools, as generally observed in the literature. Thus, the theoretical model we are building reinstates what could be seen as "traditional tools", such as paper and pencil, side by side with parametric modeling ones. This diversity of tools used, and their complementarity, are considered essential features to this model as they nurture and help the architects proceed with this back-and-forth, reflexive and iterative parametric modeling process. That way, we stress the need to keep considering in a more systematic way all the tools still relevant for architects nowadays, and in particular for those working in SMEs.

Given the observed cases in such small architectural offices, our design process model moreover builds on the back-and-forth movement observed with regard to how and when architects call for the parametric modeling tool, sometimes as a design support tool, sometimes as a representation support tool.

Our model, as illustrated on Figure 5, thus completes the four typologies of design process models schematized in Figure 1 (Blessing, 1995). It consists of a two-stage iterative process, in which the duration of each stage is independent from one another and rather depends on the architect's working method. The shift in between these two stages does not necessarily represent a temporal break but rather a change of tools. This change represents a key moment when the designer feels cognitively empowered to go further in the design process. One of the interviewed practitioners mentions using freehand drawing before starting the parametric modeling *"over the longest possible period of time, depending on the deadline"* [R2, author translation]. The transition from one stage to the other one is repeated as often as necessary. These possible iterations are represented in the model by the curved dotted arrow. This happens, for example, in order to overcome any difficulty encountered in the development of the algorithmic definition.

In our model, the first stage of iterative reflection (S1 - "emergence of the concept") is supported by one or several so-called "traditional" tools that equip the reflexive step and allow to structure the major constraints of the project, transcribing them into parameters or constraints that will be later integrated into the algorithmic definition of the parametric modeling. This stage is already part of the parametric design process per se, that will lead to the parametric model itself in the next stage. While Dino (2012) underlines the fact that parametric modeling requires intentionality and anticipation, which can lead to the phenomenon of *circumscribed thinking*, we perceive in this reflexive step rather an opportunity for designers to use other design tools to support their thinking. During this forced, early explicitation stage, architects are invited to think both in terms of designed artifact and in terms of process, i.e. in terms of definition of the algorithm. It is during - and through - that stage S1 that architects meet the requirements of parametric modeling tools, which moreover invite them to widen the field of exploration from the outset. During that stage, some of them are also observed to deepen their reflections in order to anticipate potential future variations.

This first stage is considered convergent because the architect(s) work(s) towards the definition of the guidelines of the project (in this case the input parameters Pi of the algorithmic definition), reducing in a way and for some time the exploratory field. However, the exploratory amplitude of this stage is considered to be wider than the one that could be covered when manipulating "traditional" tools only. Indeed, architects, whether they are experts in modeling or have good knowledge of how it works, now take into account the potentialities that are multiplied by parametric modeling. They thus expand the exploration of potential possibilities and allow themselves to widen their imagination. What designers allow themself to mentally represent, or allow themselves to mentally postulate as "possible", is therefore part of a wider field. As many researchers have pointed out, the digital tool that comes in later indeed encourages architects to mentally explore and represent artefacts that go beyond their own visualization and drawing skills (Kolarevic, 2005; Lee et al., 2014). The use of parametric modeling tools thus "*does not eradicate the human imagination, but rather extends its potential limits … it provides the means for exploration, experimentation, and investigation in an alternative field*" (Terzidis, 2003, p. 206).

The second stage (S2 - "parametric definition and exploration") differs from the first one by the tools used. The designer is now working on generating the parametric modeling as such. This stage is not discontinued with the first one, but rather is a smooth, logical continuation of it. This second stage is more intense in terms of iterations (as illustrated through the tighten loops) and is punctuated by the implementation of the Pi parameters that have been previously defined, and the implementation and testing of their variations. These adjustments invite new thinking, encourage a change in the algorithmic definition and so on, even going back to stage S1. These sequences are repeated until ideas are refined and reach an artifact proposal that best meets the set objectives, given the specific project and context.

This S2 stage starts from an intermediate state, either an internal representation or a representation that has been externalized via other tools. Considering it, the starting point of this second stage adjusts to Kilian's suggestion (2006), for whom parametric modeling offers only limited exploratory zone. We go further by specifying that this so-called "restricted" zone is linked to the existence of a mental image of the ongoing artifact, that is built up and drawn up little by little during the S1 stage. Starting from there, the architect then begins to draft the algorithmic definition in an exploratory field effectively limited to/by the predefined parameters (as defined in stage 1). This stage nevertheless then quickly diverges (Iordanova et al., 2009), reopening the exploratory field and the cognitive proliferation given the possibility to generate several variations. As noted by Aish and Bredella (2017), this may even enable the architect to explore beyond the design ideas originally envisioned in a way that would be impossible with traditional design and modeling approaches and which could lead to unforeseen or unpredictable design ideas (Iordanova et al., 2009; Schnabel, 2007; Turrin et al., 2011). The exact amplitude of this second cone is dependent on the capacity/willingness of the architect to reopen the field of possibilities contained in the multiple combinations of parameters. Ultimately, this stage is convergent since its goal is to choose and adjust a single design instance. Once again in S2, the amplitude of the iterative loops is considered wider than in a traditional (CAD-supported; sketch-supported) iterative process (represented in dotted line), because parametric modeling offers a widening area of exploration of the conceptual space.

In that respect, and considering our observations, we argue that parametric modeling tools should not be considered as simple drawing or model building tools, but rather are sources of representations and design alternatives that allow designers to gain new knowledge and expand the boundaries of the "solution" space that is being considered, and then explored.

6 *Concluding remarks*

This contribution is part of a larger research project that provides an overview of the current digital practices of Belgian architects (Authors, 2018) and examines in particular the practices supported by parametric modeling tools in the specific case of small architectural offices.

While some researchers conduct their research within a targeted framework (large agencies to gain insight into an established practice; experimental framework to control the analysis protocol, for instance), our objective has been to fund the research on real, day-to-day practices and the concrete needs of small architectural offices, thus fitting into a field with eclectic and unstable practices. Our research provides a reflection on how design processes evolve with regard to parametric modeling uses, and what it implies for architects working in such small offices. That way, we pave the way for further studies looking into the practices of smaller structures, considering that empirical evidence supporting an understanding of designers' behavior in professional parametric design practices is largely lacking (Yu et al., 2013).

To conduct our research we used two methods, retrospective interviews and *in situ* observations, in order to perceive and apprehend various situational aspects of a diverse set of emerging parametric practices. Five architectural agencies were thus selected as cases, and offered us the opportunity to observe more particularly the uses of parametric software based on visual programming, such as Grasshopper© or Dynamo©. The functioning of these modelers is based on a double representation of the object. If this dual mechanism of representation is powerful, it requires specific skills and a significant cognitive load from the beginning of the process. We indeed identify, through the observed cases, a process that spurs a forced and early explicitation of internal representations, as architects are required to first mentally construct the algorithmic definition of the model before visualizing the artefact per se, i.e. thinking in terms of *process* instead of *project*. This reflexive, intermediate representation step is a costly but necessary initial investment before being able to take full advantage of the added value offered by these tools.

This back-and-forth between process and project (between algorithm definition and representations of the project), thus impacts the design process more profoundly than traditional CAD tools have done. While "traditional" CAD seems to have already intensified the iterations, our results are consistent with Davis and Burry's research (2011) and allow us to consider that parametric modeling tools can further intensify these iterations, depending on the needs and objectives of the designer, but still tend to multiply the possibilities of solution-space exploration.

While some of our observations resonate with those of previous studies related to academic contexts or large agencies, our research still highlights the constant use of different tools in parallel with the parametric modeling tool. This repeated, back and forth move between design tools, and this dual use of parametric modeling as both a representation and design tool have not been clearly identify elsewhere. The fact that those two notions have not been raised in previous studies does not mean that such strategies are totally absent from other empirical or experimental contexts. They simply appear clearly when looking at architectural SME's strategies, which points to some peculiarity, hypothesized as typical from smaller structures where everyone has to work perhaps in a more multi-tasking, "multi-skills" and thus "multi-tools" approach.

Looking at those singularities, we therefore suggest to make Blessing's (1995) typology of design models evolve, and eventually propose a model that is better adapted to the observed practices in SME's. This renewed theoretical model is structured into two iterative, intertwined stages. The observation of SMEs practices leads us to detect new potentialities offered by the use of parametric modeling, particularly in terms of supporting the externalization of a mental image and placing morphological exploration at the heart of the process. Practically, we argue that parametric modeling tools and the associated thinking processes allow architects working in SMEs' to design projects that go beyond their scope of recurrent "exploration spaces", and would thus be hardly manageable without these tools.

7 Limits & future work

The results that we produce must be qualified by the limits of our methodology, which mainly relate to our desire to study the specific, emergent practices of small, or even very small architectural offices.

Considering this restricted field and given the low appropriation of parametric modeling at the present time, it has been particularly difficult to access such a field of study. Thus, one limit emerges directly from the level of parametric practice of these small offices, some of which are still under development and can therefore be considered unstable on the long-run.

Another limit relates to the choice of the cases to study, and to the questions raised by an exploratory analysis of such limited cases. Indeed, our studies reveal (through *in situ* observations and retrospective, in-depth interviews) some deep understanding of the studied object, but do not represent exhaustively all possible practices. The design process varies under multiple conditions (Lawson, 2005), and therefore the model we propose is consistent with the observations we conducted in small, Belgian offices. Our case studies also center around the uses of Grasshopper© and Dynamo©, and thus only offer a limited appraisal of the diversity of possible parametric practices.

As a result, readers moreover have to be aware that several components of our model are open to debate: the exploratory amplitudes of the S1 vs S2 stages; the exploratory amplitudes of parametric vs. traditional tools lines; the number of iterations … are all context-dependant and have been designed as to engage reflection with regard to every situated design process, rather than delineating any unrealistic, once-and-for-all crystallized image of what the design process "should" be. Those components thus deserve to be confronted later on with other design situations and other temporalities, as to ensure validation of the suggested model. Ideally, validation should also have been ensured by asking our cases' participants to review and provide feedback about the model. This unfortunately was made impossible in the realm of our specific research project, but should certainly constitute a priority task when conducting further research. Additionally, the relevance of our model remains to be tested for any extension to radically different design contexts, notably to large offices.

Generally speaking, we believe that research centred on the real needs of stakeholders ensure the development of models, methods or tools respectful of their daily practices, while highlighting dimensions and factors that can still be improved and while documenting areas eligible for potential innovations. Such research enables researchers, and in particular software developers, to be more relevant in the development of a solution and, consequently, to see the results of their work being adopted more quickly and naturally by the targeted actors. By identifying how small architecture firms are adapting to the profound digital changes that are taking place, our research paves the way towards that goal. It is envisioned that the suggested design process model may make it possible for researchers and developers to more successfully accompany SMEs through the digital transformation they are facing today.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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