COMPUTER-AIDED MODELING APPLIED TO ARCHITECTURAL KNOW-HOW: THE GOTHIC ROSE WINDOW

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EDITOR: J. M. Kamara

Nathalie Charbonneau, Ph.D. Candidate
École d'Architecture, Faculté de l'Aménagement, Université de Montréal, (Québec) Canada
email: nathalie.charbonneau@umontreal.ca

Dominic Boulerice, Ph.D. Candidate
Department of Art History and Communication Studies, McGill University, Montréal, (Québec) Canada
email: dominic.boulerice@mail.mcgill.ca

David W. Booth, Associate Professor
Département d'Histoire de l'art et d'études cinématographiques, Université de Montréal, (Québec) Canada
email: david.walter.booth@umontreal.ca

SUMMARY: *This paper explains the parameters and methodology at the heart of an ongoing research project that seeks to verify whether one can trace back the genesis of any given artefact or work of art by means of computer-aided modeling. In its endeavour our Montréal-based research team aims to initiate and propose novel methods of modeling design processes. This approach is exemplified by a case study dealing with rose tracery designs adorning Gothic cathedrals of 12th and 13th Century Île-de-France. A computerized model re-enacting their design process was developed along with an interface enabling the translation of the designer's intentions into a virtual design space. The stated goal of this research project is to evaluate empirically to what extent our modeling strategies can grasp a given artefact as a logical and articulate ensemble. Furthermore, we seek eventually to determine whether this kind of software programme would prove an indispensable tool in the development of the architectural designer's cognitive abilities.*

KEYWORDS: *architectural modeling, computer-aided design, architectural know-how, functional programming.*

1. INTRODUCTION

In the broad field of architecture, computers are currently employed to generate graphical representations of design concepts. Despite their ubiquitous presence within the discipline it is unlikely that computers are really put to use at their full capacity. Can computers be more than digital drafting tables? After all, computers literally offer a whole virtual world that can unfold in time in a non-linear fashion. With the computer one should be able to place an architectural concept before the mind not only at certain fixed moments in its development, but also in the entirety of its relational process of generation, from the mind of its creator to its material execution. Like any human artefact, a building is the result of a process, a process that is never directly accessible as a whole because its various stages cease to exist when their productive function has been fulfilled, their effects often felt only in the final product. Our purpose is not to question the value of graphical representation, the traditional medium of communication favoured by art and architecture for many centuries, but simply to ask whether computers can go beyond traditional graphical representation *stricto sensu*? Our thesis is straight forward: we argue that with certain of the technological means available today we are not always obliged to content ourselves with fixed graphical representations of design ideas isolated from one another and from formative factors in time and space. Indeed, this has been the premise of the research project this paper reports. There, as here, we explore the possibility of a computerized simulation of the various phases of an actual architectural design process by means of an historical case study, the rose window configurations of Gothic church architecture.

2. THE PROCEDURAL MODEL

Before it is materialized, an architectural idea is established, developed, and refined in the mind of the designer, though there is no trace left whatsoever of this internal mental process. Behind any given monument or artefact stands a creative process of great complexity and about which we are naturally curious. In our research we seek to determine whether the creation of any given artefact or work of art can be recovered and re-presented as a dynamic process, i.e., in its integral wholeness, by means of computer-aided modeling (Tidafi, 1996, De Paoli, 1999).

In recent years, our research team within the CAD Research Group (GRCAO), in the School of Architecture of the Université de Montréal, has sought to initiate and propose novel methods of modeling design procedures that would enable the innovative use of accumulated architectural know-how. We have explored the possibilities of developing computer software programmes that would allow the modeling of an artefact based on the know-how that produced it, thus integrating knowledge relating to its construction as well as to its formal design. Based on a procedural model, that is, a model describing an object's inherent, productive compositional logic, our modeller can not only seize and recount every step of its design process; it also permits the modeling of typological variants. Above all, such a programme not only allows, but actively encourages, interaction at all moments of the design process, particularly during visualization and manipulation of the model in the virtual design space.

3. THE GOTHIC ROSE WINDOW

Along with pointed arches and flying buttresses, medieval rose windows have come to epitomize the Gothic cathedral. From the fairly modest-sized oculi – mere roundels often left unadorned – of Romanesque and Early Gothic churches, to the colossal tracery networks spanning some 12 metres on the Western façade of Chartres Cathedral, Gothic rose windows bear witness to the great technological know-how of medieval builders (Fig. 1).

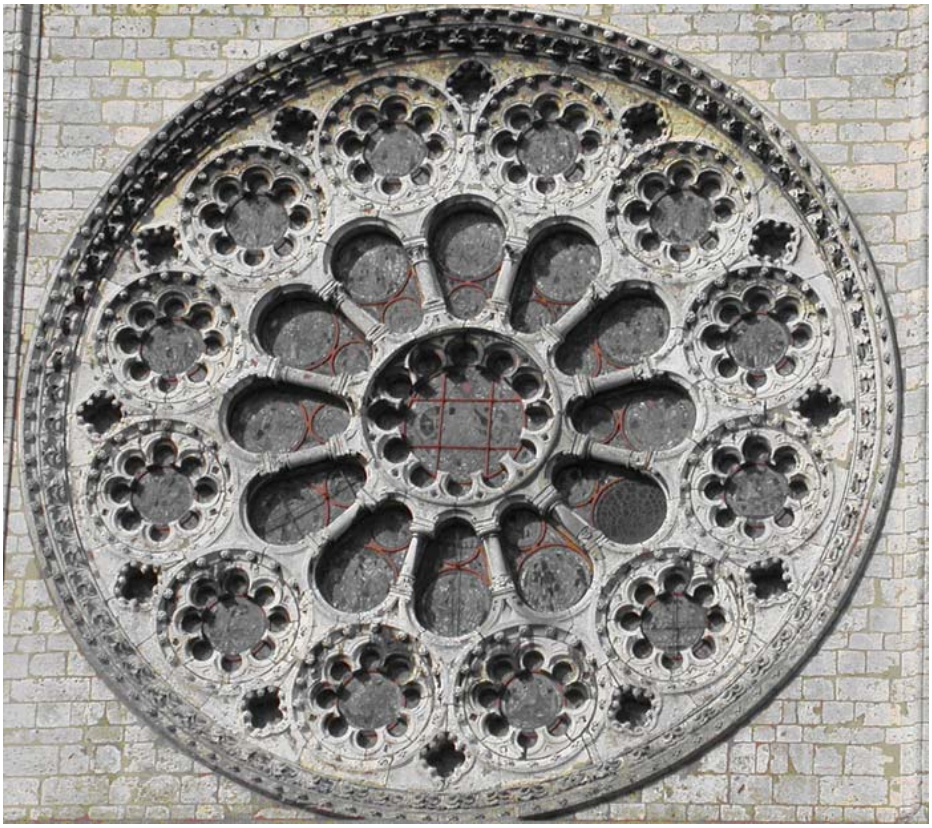

FIG. 1: Western rose window, Chartres Cathedral, photograph by Dominic Boulerice.

Tracery networks evolved from plate to bar tracery: once pierced panels of stone, they literally became thin stone bars skilfully designed and assembled to form a decorative structure supporting stained glass panels. The Early Gothic and Rayonnant (12th- to 13th-century) rose tracery designs are made up of mullions, colonnettes and voussoirs arranged according to a geometric pattern that reveals a great deal about their compositional logic. It must be borne in mind that our project seeks to trace in reverse the genesis of a given artefact, the Gothic rose window, employing a procedural model. The point of this effort is to understand, describe and model a design process that today is, at best, little-known and must be deduced from various sources, primarily the design product itself. In so doing we seek to develop a method that describes an artefact in an integral manner by modeling the relational sequence of decisions taken by its designer(s), and thereby to reveal the compositional logic that informs the artefact or work of art. Gothic rose tracery designs lend themselves particularly well to this type of compositional analysis: they were devised using straight-forward practical geometry and are basically two-dimensional in conception. They also comprise a well-circumscribed aspect of medieval design whose principles of design would have been readily grasped by practitioners who possessed little in the way of theoretical knowledge. Rose window design was not, however, an effortless art. One must never lose sight of the fact that, while these circular stone tracery networks were designed in regard of their aesthetic, formal and symbolic effects, they were also obliged to respond to mechanical problems of support and load in a manner consistent with the well-known daring of their creators. All of these imperatives of contemporary design needed to be adroitly juggled in the conception of a window tracery. Certainly the creation of such designs called for deep experience, crafty calculation, vast knowledge and outstanding comprehension of the application of structural constraints in the general context of ornamental effect, as Viollet-le-Duc correctly pointed out in his *Dictionnaire raisonné* (Viollet-le-Duc, 1854-1868).

Our working samples were chosen from among rose tracery designs of 12th- and 13th-century Île-de-France (Hardy, 1983). They range from simple oculi to double wheel-windows. Our primary interest has been to formulate the process most likely to have led to the realization of such designs, whose forms may be most easily understood as the result of the interlocking of solids and voids within an encompassing circular frame. To date, the two most basic stages of our work have consisted of, first, the reconstruction of the design process (i.e., the iteration of the compositional logic of rose window design) and, second, the making of a computer model of this process.

4. UNDERSTANDING THE DESIGN PROCESS

As with any art object, Gothic rose windows are usually perceived as global, unified *Gestalten*. In actual fact they are heterogeneous in form and material and reflect, however dimly, a complex process of creation (parts of which elude us today for having left little or no trace in their temporal wake) that was also certainly heterogeneous in the diversity of the steps of which it was comprised.

When one comes to speak of the working methods of medieval builders the evidence is rather slim. The only known architectural drawings in the modern sense date back no further than the Late Gothic period. For the earlier period we have only a smattering of full-scale working “drawings”, in the form of wall or floor tracings. These “drawings”, today few in number and often incomplete, were incised with a metal point directly onto the floor or wall of the building being constructed. Frequently, they were little more than sketches, but they also often served as working drawings on the basis of which templates for stonecutting could be made. Despite their rarity and limited function, these tracings supply us with certain precious indications as to the way designers made use of geometry in their designs (Fig. 2). Clearly, the designs were elaborated with the use of a compass, a square and a straight edge. It should come as no surprise to learn that, in the determination of their forms, medieval designers made frequent use of such well-known geometric ratios as the Golden Section and Quadrature (rotation of squares about a centre), with values respectively 1:1.618 (Φ) and 1:1.414 ($\sqrt{2}$), both obtained with simple geometrical constructions executed with compass and straight edge. Still, the most striking and compelling link between supposed medieval design methods and simple Euclidean geometry remains the traceries themselves: every facet and profile is carefully traced and cut following a strict, reproducible geometrical construction. For this reason we undertook in our project a rigorous analysis of selected tracery designs so as to reconstruct their probable geometrical matrices (Fig. 3). Although we have produced geometrical constructions describing the shape and contour of each and every voussoir, mullion and colonnette of the traceries under study, it must be emphasised that it was never our goal to replicate their exact geometrical forms, but rather to ascertain the logic of their design. Based on the evidence produced by our study, we concluded that the geometrical constructions used in every tracery design were loosely, but intelligently, adapted to the overall dictates of each individual window as determined by its designer. Thus, rather than the procrustean bed imagined by more than a few experts, it turns out that medieval geometrical method, while it furnished the designer with a repertoire of easily defined shapes and figures, and though by no means devoid of symbolic meaning, was first and foremost a flexible design tool that codified a natural way of practice.

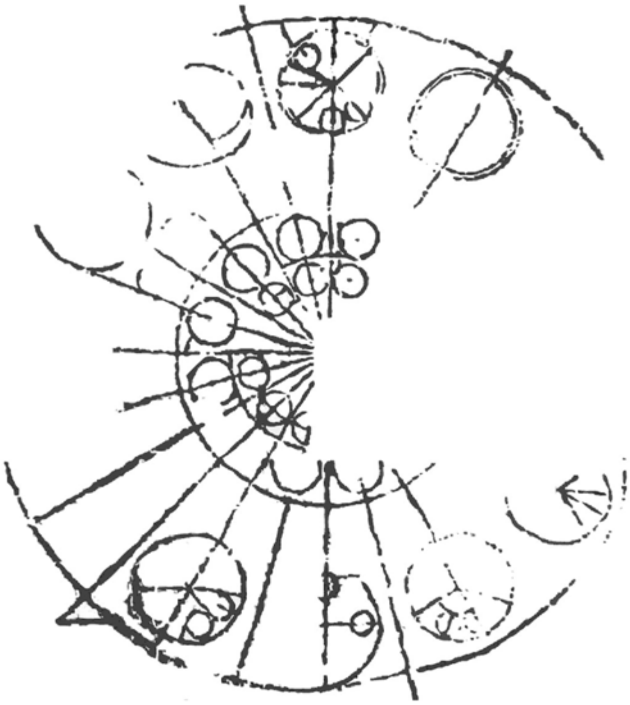

FIG. 2: Wall tracing depicting a rose tracery, South transept arm of Soissons Cathedral. Drawing after Wolfgang Schöller.

A design of any kind, while it may make use of one, is normally more than a geometrical scheme, even if only in its material realization. It may be that aspects of a design can be conveniently grasped and expressed by means of geometry, but a design is first of all an idea, the "inner" word that the mind speaks to itself (to use an expression of St. Thomas Aquinas). How can one grasp the genesis of an idea? In the case of productive ideas, that is, ideas that lead to the production of something, one can begin with that something, that product (its final cause, in the language of scholasticism), and work back from there by a process of inverse deductive reasoning. This is exactly what we have tried to do for Gothic rose designs. When reduced to its essentials, what one sees in these designs is a number of solids and voids, each of determinate shape, placed together so as to form an overall geometric pattern contained within a circular frame. All of this may be conveniently expressed in mathematical terms but, as Booth pointed out: "[…] what counts in architecture is not the mathematics *per se*, but the perception of the forms, patterns and relationships that mathematical representation helps to bring before the eye" (Booth, 1996). As noted above, we found that, in medieval design, abstract geometrical schemes are readily adapted and adjusted to the exigencies of individual designs, and we concluded that traceries were modeled according to visual, perceptual imperatives rather than those of strict geometry or mathematics. Like his brethren in other ages, the medieval designer was primarily concerned with furnishing a qualitative, rather than a merely quantitative, experience.

A medieval designer had to consider many issues in designing window tracery, including those chiefly of aesthetics, symbolism and construction. In reconstructing the rose design process, we needed to establish the various decisions taken by these designers and to arrange them in a logically interrelated sequence reflecting the increasing complexity evident in the historical evolution of the building form without becoming so attentive to particulars that we "failed to see the forest". This was tantamount to formalizing the know-how at the heart of Gothic rose tracery design. For each visual element of a representative example it was necessary to reproduce by means of deduction, reasoning from the known to the unknown, the pertinent knowledge and understanding of their makers adduced by Viollet-le-Duc early in the 19th century. Although it was never our purpose to quantify the physical forces present in the tracery networks that form the subject of our study (something that remains a theoretical possibility), one simply cannot truly understand their forms without giving due consideration to the jointing and assembly of the masonry elements of which they are made. As James clearly states, “the joints in the stonework are an important part of the design. They are never placed accidentally” (James, 1973). In fact, Gothic rose tracery could justly be viewed as the result of the interplay between formal and constructional considerations. It is for this reason that we put forward certain hypotheses relating to the jointing and assembly of the flat plates, voussoirs, mullions and colonnettes that make up tracery networks, even though our main focus remains on the design process in the larger sense.

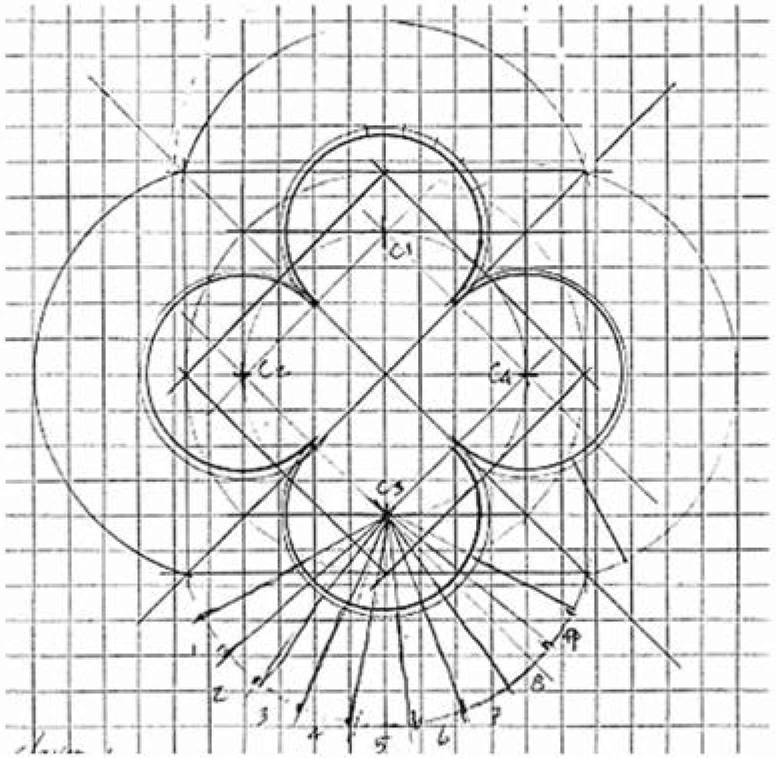

FIG. 3: Geometrical study of quatrefoil (Oulchy-le-Château). Drawing by David W. Booth.

5. DEVELOPING THE SOFTWARE PROGRAMME

We should like to emphasize that we developed a rose typology by grouping the elements of the representative examples in accordance with their logic of assembly, and not according to visual similarities, as is normally done in stylistic studies. It goes without saying that this type of classification based solely on the logic of shape was not meant to reflect the historical development of Gothic tracery designs. By moving beyond descriptive aesthetics and into technical/constructive factors we were able to advance our understanding of the design logic of rose window traceries, a clear instance of the advantage of a procedural model that never loses sight of the interdependence of all design decisions. We realized, for example, that the joints of flat plate roses adhere to a rationale unrelated to that governing the joints of what we call wheel roses. For example, the rose windows of the South transept arms of the churches of Saint-Étienne in Beauvais and Notre-Dame-en-Vaux in Châlons-sur-Marne, both from the second half of the 12th century, employ radically different jointing schemes. While the tracery design of Notre-Dame-en-Vaux appears to be an abridged and incomplete version of the wheel window of Saint-Étienne, that is, a multifoil missing its eye and radiating colonnettes, it is in fact not so. The rose window of Saint-Étienne in Beauvais belongs to what we designate the “wheel” category, because all the joints of its voussoirs radiate from a unique central point, that is, the eye of the wheel. The rose window of Notre-Dame-en-Vaux in Châlons-sur-Marne, on the other hand, belongs to the flat plate category, since its joints radiate from 4 peripheral centres each located in the centre of a different foil (Fig. 4). This turned out to be a fundamental distinction that allowed us to classify any rose as belonging to one or the other of two basic categories. On this foundation, we then identified similarities and differences among the chosen examples representative of our typology and established the variables to be taken into account, namely, morphology, relative dimensioning, reciprocal positioning of components, etc.

FIG. 4: Rose window of South transept arm, Saint-Étienne, Beauvais (left) and easternmost rose window of South transept arm, Notre-Dame-en-Vaux, Châlons-sur-Marne (right), photographs by Dominic Boulerice.

Based on our analysis of representative historic examples, we put forward a number of hypotheses in regard to both the type and sequence of decisions faced by medieval designers. There are undoubtedly many ways one could go about representing the process of designing a rose window. However, if they are to be accurate, none of these ways should represent the process as consisting of a linear sequence of decisions, but rather of a nest of interrelated questions and answers that ascend and descend as in a spiral. To model such a complex design process we chose to exploit a systemic approach, which expressly allows one to take into consideration not just the entirety of a designer's decisions, but, more importantly, also their mutual dependence (Le Moigne, 1990). Such relationships of dependence were key elements in the modeling of the rose tracery networks, since they defined the logic of the whole design process.

For example, we reason that the designer of a Gothic rose must have begun his composition with a circle of a certain size, that is, the circle delimiting the perimeter of the tracery network. Logically, he would then most likely have chosen the basic type of rose – oculus, multifoil or wheel – each of which is parametrically defined by our system. Subsequently, he would have decided how many foils or segments, as well as the type of decoration. These are just a few of the more important questions, posed by the system as imperatives, that form the basis of our model of the medieval design process and that we believe explain the various observable rose formulae. Our effort was directed toward the establishment of parameterized descriptions of all possible outcome scenarios as determined by our analysis of representative examples such that a single model uniting all identified procedures would result.

Scheme, a well-known functional programming language, permitted us to efficiently describe any given type of rose in the form of a procedure. The code could then be exported for visualization into a CAD programme, such as POV-Ray. By changing the value of the variables, given in the form of arguments, it was possible to generate different tracery designs that yet belonged to the same type.

For example, with our programme it is possible to create any multifoil – a trefoil, a quatrefoil, a sexfoil, or whatever – with an identical procedure, since all multifoils are described by the same code. Similarly, a single-wheel rose with eight colonnettes invokes the same procedure as would a double-wheel with 36 colonnettes. This way of modeling has lead to some unexpected but intriguing results, such as the recognition of an identity of organizational and functional logic between the roses of Noyon Cathedral and Notre-Dame in Paris (Fig. 5), an identity not to be expected on the basis of visual examination alone.

The establishment of these variables along with hypotheses concerning the sequence of decisions taking part in the design process led to a first, trial version of the procedural model. The flexibility of this first model was, and still is, tested by substituting different values for the variables in order to see if it is always possible to describe each of the elements supposedly belonging to a given type. When we deem it impossible to adapt an existing procedure to include the description of any element, the latter is regarded as belonging to another type, calling for an additional procedure. Our objective at this stage of the analysis was to create a procedural model easily able to include the description of all the elements belonging necessarily to a given type. In other words, we grouped together all forms that can be generated from the same set of procedures. With this goal in mind, the programming code is used as a classification system, literally a “data-processing typology”, by which visually dissimilar architectural elements can be classed as of the same type if they all meet the functional criteria that define that type. For example, we counted many different types of cusped voussoirs, but since they all carried out the same function, they were classed as of the same type.

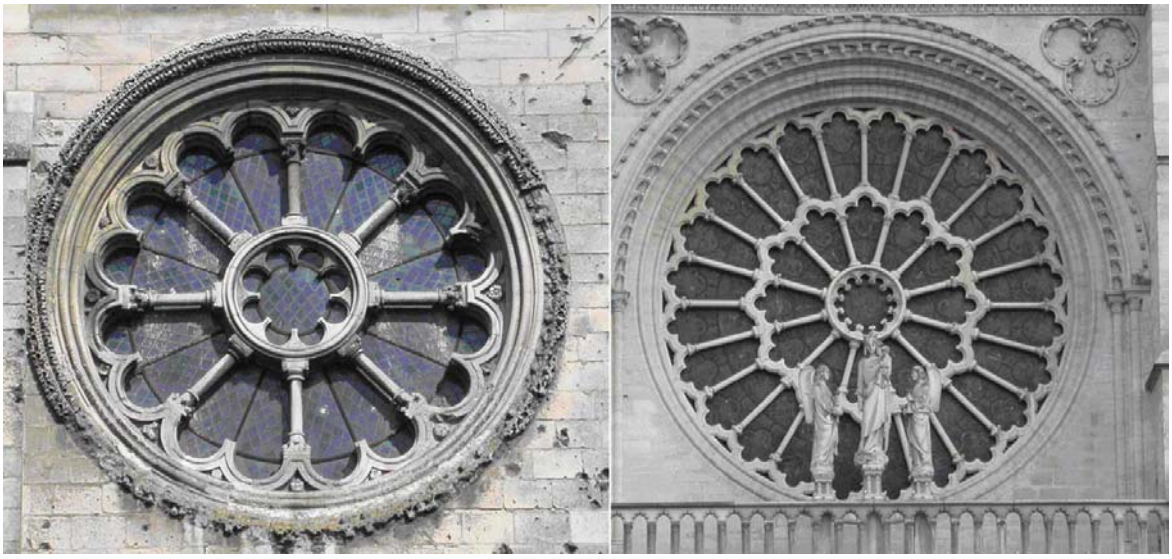

FIG. 5: Eastern rose window, Treasure Room of Noyon Cathedral (left) and Western rose window, Paris Cathedral (right), photographs by Dominic Boulerice.

By using the data-processing typology, we intend to describe an ensemble of artefacts in the clearest and simplest way. In fact, our programming code is thereby optimized. As Springer and Friedman argue, “in programming, perhaps more than in other arts, less is more. Simplicity is nowhere more practical than in programming, where the bane is complexity” (Springer and Friedman, 1989). The flexibility of programming code is such that, potentially, it can be constantly developed. We took advantage of this aspect of programming by initially taking into account only a relatively limited number of artefacts. As our study advanced, additional artefacts are successively incorporated into what is in reality a federative model. The fact that the type and number of variables given as arguments in the procedures can be altered easily is fundamental. Indeed, the successive addition of elements drawn from our historical study leads to the continuous testing and refinement of the developing typology. Since modeling (encoding) is an iterative process, the great plasticity of the procedural model helps minimize any unnecessary expenditure of time and energy. As Lévy put it: “a model constitutes only a stage, a moment in an uninterrupted process of tinkering and intellectual reorganization” (Lévy, 1990).

Our software programme – at the time of writing, still under development – is adapted from the procedural model that constitutes its core. The programme is structured so as to “re-enact”, so to speak, the series of choices and decisions that we believe once gave rise to Gothic rose window traceries.

Thus, our software programme allows its users a certain exploratory liberty in what may be called the design space of the Gothic rose. It has been developed to generate representations of rose traceries by means of an unfolding, interrelated series of decisions. As a truly heuristic tool its function is twofold: first, to emulate every stage of the medieval rose window design process; and, second, to visually transpose the designer’s intentions to a virtual design space.

At each stage of the virtual design process, the screen presents various pictograms representing different design options and alternate pathways from which the user may choose. A choice is made by simply clicking on the pictogram (in reality, a button) representing the desired option. Since every choice is linked, earlier choices condition all subsequent ones, and the design space is conceived as an arboreal structure in which users can freely navigate – upward or downward, much as medieval designers must have done in pursuit and formulation of their design goals. At the end of every branch of the structure, the user may generate a 3D model presenting a sum-visualization of choices made up to that point in the design process. These digital models give users the possibility of apprehending complex 3D objects in virtual space, as well as the option of viewing various components from different angles so as to better grasp the consequences of their actions and the evolving morphology of their designs. It is, in fact, possible for a user to design an authentic Gothic rose window irrespective of whether it corresponds to an actual historical example, or represents something that has never before seen the light of day. In either case, the rose will have been conceived according to the medieval know-how codified by the system (Fig. 6).

By way of illustration, let us suppose a user of our software programme who wished to design a rose window similar to the South transept rose of Notre-Dame-en-Vaux in Châlons-sur-Marne, as seen in Fig. 4. The procedure would be as follows (square brackets indicate option selected in each instance):

- Type: oculus, [small], medium or large tracery window;
- Category: [flat plate] or wheel rose window;
- Number of foils: 3, [4], 5, 6 or 8;
- Foil type: regular, semicircular, segmental or [horseshoe];
- Foil orientation: along a [vertical] or oblique axis;
- Profile: [fully chamfered], inside chamfer, outside chamfer, straight;
- Spandrel ornamentation: [without], circle, trefoil, reversed trefoil, quatrefoil (type 1 or 2) or openwork.

After having gone through this particular sequence, the user would have designed the rose tracery design of Châlons-sur-Marne as seen in Fig. 6 in the interface of our software programme and halted during the seventh stage of the design process where the user is asked whether he wants to ornate or not the spandrels of the rose with a specific motif, all of which are presented to him as pictograms on the face of buttons located below the main window showing the 3D model. The user's path into the arboreal sequence of the procedural model is represented on the upper left hand side of the interface. At any time during the design process the user can therefore not only backtrack any of his actions, but also access documentation on Gothic rose windows, documentation designed to stimulate a deeper understanding of the subject and consequently aid him in designing traceries.

A few remarks concerning the arboreal structure of our procedural model and its relations to tracery design are in order. At the point of the initial interrogation regarding the choice of general rose window type, it is reasonable to encounter the question of overall size (small, medium or large). Indeed, we realized that the question of size is fundamental in determining all types of rose windows. Historically, oculi or roundels are the smallest roses ever built, the larger ones always sporting tracery and stained glass panels. Among the many historical examples, we ascertained four basic sizes of rose window (represented schematically in the interface) which are, in ascending order: the oculus; the small tracery rose window (e.g., Noyon and Châlons-sur-Marne); the medium size tracery rose window (e.g., Beauvais); and, finally, the large tracery rose window (e.g., Chartres and Paris). As we noted earlier, circular tracery designs employ one or the other of two jointing patterns: that of the flat plate rose window, where the joints radiate from multiple peripheral centres, or that of the wheel rose window, where every joint radiates from a single central point. This, then, is a fundamental distinction in our typology. Not surprisingly, the number of foils a rose window may have, another important distinction, is relative to its size: a small circular tracery window never has more than 8 foils; a large one may have as many as 10 or 12, but never less than 8. As to foil types, they are a direct function of their number. It seems medieval designers particularly favoured the quatrefoil, having proposed up to four variants of the type. The fact is that, based on a square (frequently pivoted about its centre), the quatrefoil lent itself easily to simple geometrical manipulations. It is also noteworthy that the orientation of an entire window can be defined by the placement of its "head" foil, that is, according to whether the topmost foil is or is not aligned with the vertical axis of gravity. The jointing rationale was evidently a consequence of the overall orientation, since, from the point of view of stability, a joint would normally never occur in the cusp of a voussoir, but rather in the mid-point of a foil. Finally, the ornamental part of the design was largely a matter of selecting and shaping the various profiles and incising the faces of the voussoirs.

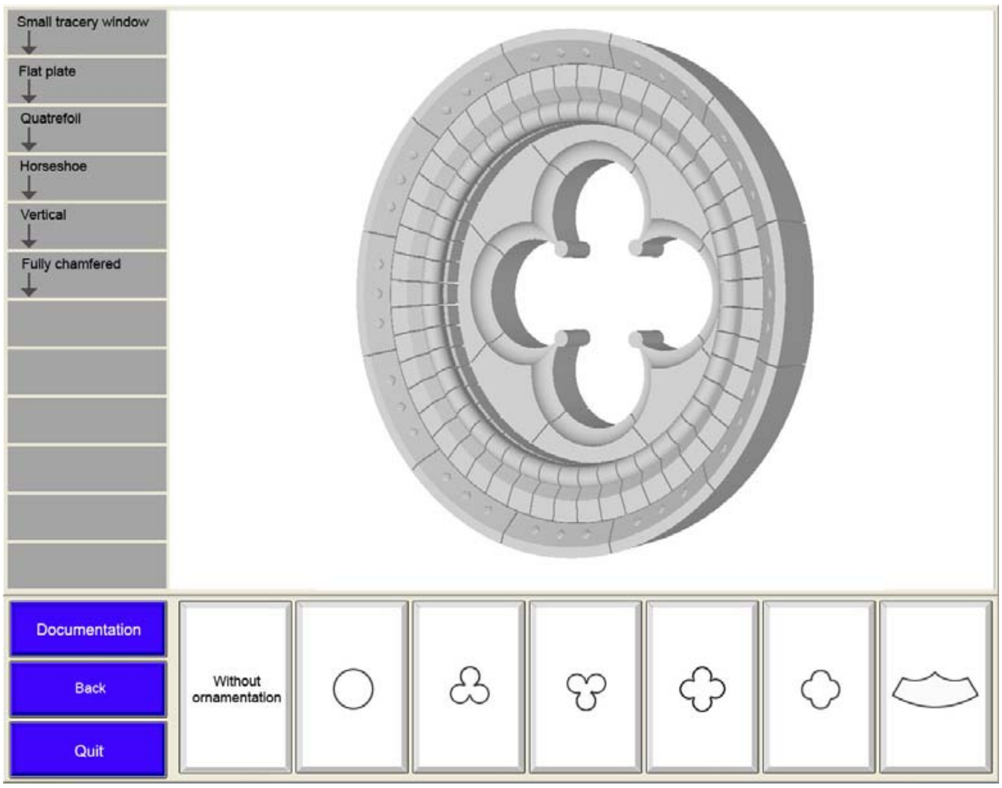

FIG. 6: Software programme interface.

So far, we have seen how a user can navigate through our interface and we have explained the inherent logic of our software programme based on the design knowledge exhibited in Gothic rose traceries. To illustrate more clearly how this knowledge could be translated into concrete procedures, we reproduce below the procedural code for the creation of the oculi, a procedure that permits multiple variants, as seen in Fig. 7: a roundel (a); a chamfered oculus with and without a trim (b and c); and three quatrefoil-shaped windows, each with a different trim, moulding and jointing scheme (d, e and f).

```
(define rose
  (cond
    ((= type-oculus 0) (ocuNonExt))        ;oculus with no extrados
    ((= type-oculus 1) (if (= 1 trim-type) (ocuExt)        ;oculus with no trim
                           (shpUnion (ocuExt) (trim))))    ;else with trim

    ((= type-oculus 2) (cond    ;quatrefoil

                         ((= type-quatr 0)      ;Oulchy type
                         (cond ((= 0 moulding-type)  (quatr0 mould0)) ;with moulding 1
                               ((= 1 moulding-type)  (quatr0 mould1))  ;with moulding 2
                               ((= 2 moulding-type)  (quatr0 mould2)))) ;with moulding 3

                         ((= type- quatr 1)      ;St-Medor type
                        (cond ((= 0 moulding-type)  (quatr1 mould0))   ;with moulding 1
                              ((= 1 moulding-type)  (quatr1 mould1))   ;with moulding 2
                              ((= 2 moulding-type)  (quatr1 mould2)))) ;with moulding 3

                         ((= type-quatr 2)      ;Nanteuil type
                         (cond ((= 0 moulding-type) (quatr2 mould0)   ;with moulding 1
                               ((= 1 moulding-type) (quatr2 mould1))  ;with moulding 2
                                   ((= 2 frame-type)  (quadri2 fr2))))));with moulding 3
    ))
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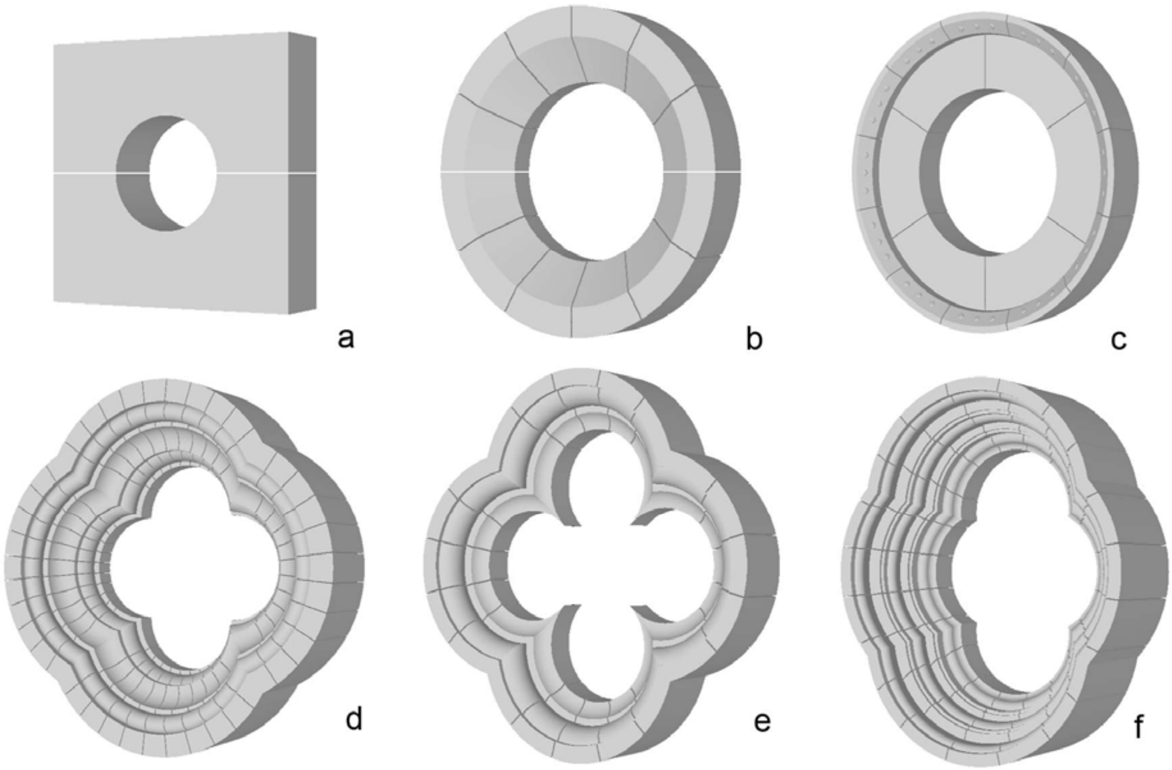

FIG. 7. 3D Models of rose windows: (a) roundel; (b and c) chamfered oculi with and without a trim; and (d, e and f) three quatrefoil-shaped roses with different trims and jointing schemes.

As our software program is still under development, the category of the colossal double wheel window (Chartres and Paris) awaits further definition. However, since members of this group employ the same logic that governs the smaller flat plate or wheel rose windows, their codes will be adapted from the latter and amplified. To date, our software programme has proven capable of generating a wide variety of rose tracery designs, ranging from the oculus to the openwork multifoil. Fig. 8 depicts a flat plate quatrefoil (a), an openwork quatrefoil (b), an eight-lobed oculus (c) and a plate tracery rose window (d).

In addition to further development of the software programme itself, we should like eventually to undertake an evaluation of its usefulness in the development of the cognitive skills of art history and architecture students: to what extent do such programmes really help users to grasp a given artefact, in this instance the Gothic rose window, as a logical and articulate ensemble?

We are inclined to believe that the use of a procedural model will favour the acquisition of knowledge. As Basque has noted, simple access to information does not necessarily lead to knowledge. Cognitive sciences invite us not to mistake "information" and "knowledge"; knowledge requires mental effort, the making of meaningful connections between what are otherwise merely discrete bits and pieces of information (Basque, 2003). In a word, what makes the difference is understanding. It is hoped that our completed software programme will help users to better understand medieval design by helping them to see it as a dynamic process comprised of many decisions meaningfully and consequentially interconnected. Experience is fundamental in knowledge acquisition. The problem with traditional, linear expression is that in matters of design it frequently relegates the subject to a passive, contemplative mode of learning. By contrast, expressions that use virtual space simulate visual aspects of reality and, when they take a form such as our programme, consistently demand the active participation of the user. We believe that by organizing and presenting information in other forms than that of linear text, tables or figures, our software programme complements traditional ways of learning. Perhaps in arranging information in accord with a different logic, procedural models will promote what Lévy has called "knowledge by simulation" (Lévy, 1990).

We should like to emphasize that the software programme we have developed is not an automatic generator of rose traceries; the user is a true designer whose input is determinative at every stage of the design process. The software has not been designed to perform the mechanical application of a set of rules in accordance with a predetermined sequence, but rather to suggest available alternatives that help orient the user in his/her decision-making within the established parameters of rose window design, and to provide timely visualizations that assist the user in understanding the design implications of his decisions. The layout of any rose in process of design follows the sequence of decisions made by the user. We agree with Mitchell when he states that, "choices among possible responses might be made mechanically but this is not characteristic of skilled human designers. Critical reflection on the entailments of possible responses normally lies at the heart of architectural design process" (Mitchell, 1990). Accordingly, the users' critical reflection should always be at the heart of the computer-assisted design process; what is needed is what Schön called "reflection-in-action" (Schön, 1983). Computers are machines, but programmers are not.

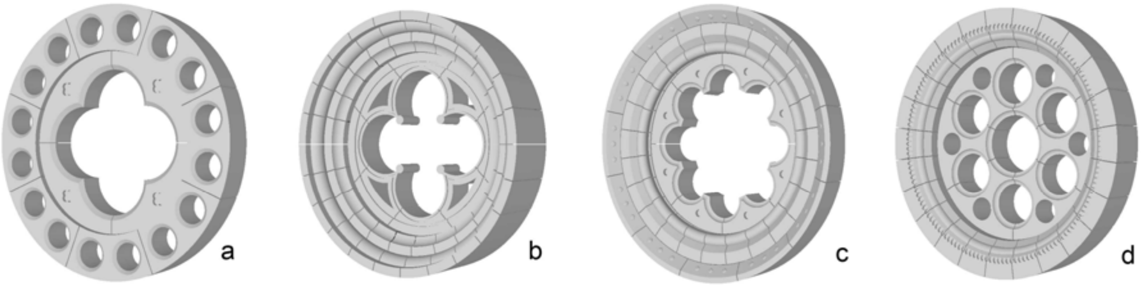

FIG. 8. 3D Models of rose windows: (a) quatrefoil; (b) openwork quatrefoil; (c) eight-lobed oculus; and (d) plate tracery.

6. CONCLUSION

The procedural model we have developed has proved highly effective in modeling Gothic rose tracery designs in accord with traditional medieval know-how. While such know-how can never be replicated, our research shows that viable modeling strategies can unquestionably be derived from it. By developing an approach based on the modeling of a given design process, we sought to achieve two primary objectives: first, the development of introductory software programmes, each based on a different architectural know-how or construction technique; and, second, the deployment of this software as a complement to more traditional pedagogical material in didactic contexts where art and architectural students could profit from a fuller approximation of the actual experience of the creation of architectural works of art.

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Head researcher: Chantal Hardy, Associate Professor, Département d'Histoire de l'art et d'études cinématographiques, Université de Montréal; Co-researchers: David Booth, Associate Professor, Département d'Histoire de l'art et d'études cinématographiques, Université de Montréal and Temy Tidafi, Associate Professor, École d'Architecture, Université de Montréal.

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