Knowledge Acquisition in Parametric Model Development

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This paper addresses the development of parametric models in contemporary architectural practice. A parametric model can be regarded as a representation of a solution space and in order to structure this, a description of the problem is required. Architectural design tasks are typically ill structured, the goals may not be defined and the means unknown. Moving from an incomplete problem description to a functional parametric model is a difficult task. This paper aims to demonstrate that through a combination of knowledge acquisition and capture a parametric model can develop from an incomplete problem description. This demonstration draws on existing strands of design theory which are then used to outline a theoretical framework. This framework is then used to examine a case study of a live project and practical examples of the described theory in action are given. The practical observations are the result of a case study involving the author as a participant and observer working with HOK Sport to develop a cladding geometry solution for Lansdowne Road Stadium in Dublin.
1. INTRODUCTION

The potential benefits of parametric tools in practice have been acclaimed, while simultaneously acknowledged as increasing time required and complexity of design tasks [1, 2]. The establishment of specialist geometry and modeling groups within architectural practices [3, 4, 5] suggests an increase popularity of parametric design in architectural practice. The potential benefits of parametric tools are demonstrated by the work of these specialist groups. Parametric modeling has enabled the capture and rationalisation of design intent [4, 6]. Building design and construction documentation solutions have been developed using pre-rational and embedded rationale [7, 8, 9]. Multiple design alternatives can be generated and evaluated in terms of various criteria and better solutions selected [9]. Evaluation methods require different design representations which establish new links with other design disciplines [8, 9]. Parametric design has enabled the exploration of complex geometry [10] and deeper exploration of traditional design methods [11]. These examples demonstrate the potential of parametric design through descriptions of detailed stages of design and documentation, but the means for arriving at that final parametric model is often not explored. It is proposed here by systematic study of the process of parametric model development the observed complexity associated with the task can be reduced.

Some of the increased complexity and time required for parametric design can be attributed to the need for the understanding of the technology and learning of technical skills. The cognitive problem of explicitly constructing a solution space or a problem description is considered a more significant issue. Design tasks can be classified by understanding how complete the problem description is. Architectural problems typically can be described as ill structured tasks or even wicked problems [12, 13]. These types of problems consist of unknown goals and means, whereas well structured design tasks have goals that are clearly defined and the possible means for pursuing those goals unambiguously stated.

The process of developing parametric models has been described as “meta design” [14] or “design of design” by Mark Burry. Burry and Maher [15] suggest that everything needs to be considered or known at the outset of a parametric design process. It is suggested here that the opposite may be true, the process of developing a parametric model can begin with incomplete knowledge of the problem. A key part of the process is therefore obtaining knowledge of the problem and using this to structure the problem space. Simon [12] identified that the structure of design problems could develop through continuous modification of the problem space. The task of finding and describing problems as well as solving them has been identified and observed as one of the primary roles of a professional practitioner. Reflection in action [16] is the process of
conducting small mental experiments and evaluating the results in order to gain understanding of a problem. Parametric tools can provide an explicit means of conducting reflective tests that enable knowledge acquisition in order to develop and structure problem descriptions.

Research into design problem solving and the role of artificial intelligence in design provides detailed descriptions of problem solving methodologies [17, 18, 19]; a key component to these is the role of knowledge in design. These methods are aimed at problems from a mechanical engineering origin where the goals and means are well defined at the outset. In this paper aspects of these design methodologies are used to examine an ill structured architectural design development task.

2. CASE STUDY DESCRIPTION

Lansdowne Road Rugby Stadium site was highly constrained by boundary conditions (Figure 1 top left and right). These dictated rights-to-light planning restrictions and horizontal expansion limits defining a possible volume for development. Internally 50,000 seats and a natural grass pitch were required. The combination of these factors along with a desire for a recognizable form led to a proposed design with double curved envelope geometry which acted as a design surface which defined structural roof geometry. While the development and control of this geometry was developed parametrically it is not the focus of this paper (see [20] for a detailed technical description and [21, 22] for a general theoretical overview of the parametric modeling of Lansdowne Road). This paper focuses specifically on the cladding design task (Figure 1 bottom left and right) and how this relates to a body of design method theory.

3. KEY THEMES FROM THEORY

In this section a series of key theoretical themes from existing literature are identified and described. These themes focus on the role of knowledge in design. It is proposed that this may form a basis for a theoretical framework.
for the process of parametric model development. First some of the various roles of knowledge are outlined, followed by a description of a theoretical knowledge representation schema called “design prototypes”. The proposed working method for design with “design prototypes” is then described; this involves initiation and then refinement through iterative cycles. The cladding design task for the Lansdowne Road stadium project is examined in light of these key theoretical knowledge based themes.

3.1. Knowledge

The role of domain or task knowledge (experience or heuristics) is a theme that extends across much of the literature on problem solving and parametric design. Design itself has been defined as a “knowledge based problem solving activity” [17]. While some practice based observations have found that design proceeds in a series of fragmented heuristic episodes [13]. Newell, Shaw and Simon [23] define heuristic as “any principle procedure or other device that contributes to the reduction in the search for a satisfactory solution”. Successful application of heuristics to design tasks in architecture is dependant on an individual’s ability to select a suitable heuristic from a memory of previous design tasks. That memory can only be assembled through experience and the ability to select from it is governed by lateral identification of similar characteristics between the current task and those in the memory.

The ways in which domain knowledge can improve efficiency in design have been identified [18]. Knowledge can be used to reduce the complexity of problems by ruling out ranges of possible solutions. Identification of key parameters (those having greatest effect on design) from the multiple parameters reduces the amount of searching. Further reduction in search can be achieved by knowledge of valid ranges of key parameters.

It is proposed here that parametric tools can provide a representation for capturing existing knowledge and acquiring new knowledge. The process of knowledge acquisition is regarded as equivalent to exploration. Exploration as a method of design has been discussed [17, 24, 25] as a means of discovering new functionality, constraints and parameters and suggesting how an existing problem description can be adjusted or discarded. The reflective mental experiments observed by Schon [16] are examples of implicit exploration conducted by professionals aimed at gaining new knowledge of a problem. In this paper parametric design is regarded as an explicit means of conducting these kind of experiments.

3.2. Knowledge Representation

Gero [19] has described a knowledge representation schema for design which he calls design prototypes. Called prototype because it is the first on which others are modelled. The aim of the prototype is to bring together all requisite knowledge appropriate to a design. Here problem descriptions are
broken into three main interconnected parts; function, structure and behaviour. 1) Function relates to the intention or goals of the artifact. 2) Structure comprises the parts or components that the artefact will comprise of. 3) Behaviour concerns that way in which the structure achieves the function. The process of window design [26] is described in terms of the design prototype. Some of the functions of this problem are to provide daylight, control noise and provide views. The structure in this design problem comprises of glass and frame. The structural components have variables such as frame dimensions and glass coatings which determine their behaviour. Two of the behaviours of the structure are light flux transmitted and sound reduction.

Different aspects of knowledge are recorded in the prototype system determining the relationships between function, structure and behaviour. Gero describes this knowledge in terms of context, relational computation and qualitative. Context knowledge relates to external variables. Relational knowledge determines to dependencies between function, structure and behaviour, while computational knowledge represents the ability to express these relationships as code mathematically. Qualitative knowledge provides information on the affects of adjusting variables. Gero’s design prototypes are formal and aimed ultimately at implementation in an automated system. However they also provide a cognitive model for tackling and analyzing the development of parametric models.

3.3. Design with Knowledge Representation

Gero proposes that design with prototypes is initiated through case retrieval or by specifying an initial set of function structure and behaviour [19]. The starting prototype is based on analysis of the clients functional specifications and is retrieved from memory or structured based on an existing solution or a solution from a similar problem. Drawing an analogy between the current problem and previous solutions in the designers memory has been described as case based [18], recall [25] and case retrieval [17]. This is consistent with other theories of design where heuristics have been observed in practice [13] to initiate a design process. While some cases may be drawn from human memory others may come from more formal libraries like the repository of design patterns [27, 28], or the referents library described by Iordanva [29]. A prototype retrieved from memory is then adapted to suit the new condition. The adaptation is based on analysis and knowledge of the new condition, the adapted prototype then becomes the starting point for the design problem. An initial solution can be synthesised and then evaluated to see if it achieves the functions defined by the prototype. This tripartite model of analysis-synthesis-evaluation generates new knowledge of the problem which either leads to reinterpretation of the analysis, synthesis of a new solution or reformulation of function and constraints of the problem. Other cyclic models have been proposed; propose-critique-modify [17] and divergence-transformation-convergence [30] both can assist in developing an initial
problem description. The development of the model therefore progresses cyclically and knowledge of the problem increases. At each loop the appropriateness of the described function, behaviour and structure can be assessed. Based on this assessment new knowledge is acquired which is then used to change, omit or add goals and constraints.

4. DEVELOPMENT OF LANSDOWNE ROAD PARAMETRIC CLADDING SOLUTION

The cladding design task for Lansdowne Road Stadium can be described as ill structured. The only constant in the problem was the geometry of the underlying structure (Figure 2 left). The geometric, material and functional goals of the task were undefined and the means for achieving those goals unknown. The description of the development of the parametric model is organized around a series of iterations each representing a chunk of knowledge acquisition. Each of these iterations can be further decomposed into a series of smaller lower level loops.
4.1. First Iteration - Initial Studies

The cladding design began with incomplete knowledge of the problem. In terms of the “design prototype” the cladding design process started with the function of covering underlying geometry. The structure of the problem comprised geometric primitives; points and four sided polygons (Figure 2 right). These would be located on the underlying geometry which consisted of curves in planes, which describe the centerline of each mullion (Figure 2 left). Variables defining the behaviour of the structure were point spacing, starting positions for points, directions for spacing points on the curves and a boolean switch which forced twisted polygons planar. A variety of setting out alternatives were generated (Figure 3) that incorporated both planar and twisted panels (Figure 4 right). Satisfying the initial function was trivial; several alternatives were produced and evaluated by the design team and clients, knowledge of their aesthetic preferences was acquired.

Initially computational knowledge was restricted to what could be achieved with predefined tools with the chosen parametric software. This limited solutions to rectangular arrays of panels. Aesthetic evaluation determined a requirement for ragged arrays of panels (Figure 3 right), computational knowledge was therefore developed to satisfy this requirement.

This initial design phase included developing a means to evaluate the underlying geometry. Two functions were added to indicate; rainwater runoff over a single panel (Figure 4 left) and areas of greatest surface curvature. A line and circle were added to the other primitive structures of the cladding problem, the centroid of the polygon representing each panel determines the line start point and circle centre. The fixed length line behaves so its endpoint lies on the panel and at the lowest possible position, indicating rain water runoff direction. The behaviour of the circle is that it only exists if the out of plane dimension (twist) of the panel exceeds a preset maximum. The final function added to the model at this stage was to layout all panel outlines in one plane with individual identification tags. This was to establish and test some basic methods of processing model information for production.

4.2. Second Iteration – Manufacturing Constraints

Meetings with potential manufacturers introduced context knowledge in terms of construction and financial constraints. This knowledge provided a fuller description of the problem, the specificity of which greatly reduced the range of possible solutions. The function of the cladding was defined as a rainscreen, an inner façade would handle full weather proofing of internal spaces. In terms of task structure the simple point and polygon components were replaced with a more complex set of geometric elements representing a sub-assembly of the panel. Two alternative assemblies were proposed by the
design team, a glass panel and a folded polycarbonate assembly (Figure 5). Selection of two component assemblies was a heuristic step, the decision was informed by fabrication experience and aesthetic preference. Knowledge acquired from manufactures determined maximum component dimensions and that all panels would be planar. This heuristic step reduced the range of possible solutions by decision making based on manufacturing experience.

4.3. Third Iteration – Developing Composition and Method

The previous stage had established in detail the structure and function of the cladding design task, the next model development iteration loop involved developing an understanding of the behaviour of the structure and expressing this in a computational manner. While the structure for panel assembly was known, the method and components for fixing panels back to mullions was undefined. The function of these fixings was known and financial constraints demanded a standardized system with the ability to support the panels over the double curved geometry. Based on this functional understanding a double arm bracket system was proposed that incorporated two axes of rotation (Figure 6). The behaviour of this component determines how the cladding system fits the underlying geometry. It can be described in terms of the neighbours left and right of the bracket. Two angles are required to position the bracket (Figure 7 and 8). Angles are relative to an initial bracket position which is normal to and in the same plane as the mullion. The first angle can be considered a plan rotation (Figure 8 top) which rotates the bracket around the mullion to give equal angles to left and right neighbours. The second angle rotates the bracket around its face to give equal angles to left and right neighbours (Figure 8 bottom). Given a tangent to the mullion curve and a vector between two brackets the panel plane is defined. To apply this iteratively to all 4000 brackets knowledge was required to develop a computational expression of this algorithm. Several algorithms were developed, each of which was evaluated to see if it satisfied the specified function.

Once techniques for positioning the brackets were acquired both panel options were evaluated. Rendered images were used for aesthetic evaluation.
Figure 6. Double arm bracket rotation axes. Left: Initial position. Middle: Rotation around mullion. Right: Rotation around face of bracket.

Figure 7. Double arm bracket positioning.

Figure 8. Double arm bracket positioning. Top: Rotation in plan. Bottom: Rotation in elevation.
and a quantity surveyor conducted a basic costing using bills of quantities extracted from the model. Based on these a final assembly was chosen.

4.4. Fourth Iteration – Façade Ventilation

The need for ventilation through the façade provides a concise illustration of the cyclic process of propose-critique-modify in parametric design. In terms of the cladding design prototype knowledge of structure is well defined as the geometric representation of panel assemblies, behaviour of these is already well established. Ventilation requirements add further aspects of function to what has already been described. The cladding design had to provide ventilation to intake and exhaust for several plant rooms containing air handling units along the perimeter of the fifth and sixth floors. This was achieved by adding a behavioural variable that defined a rotation angle applied to panels along their long axis (Figure 9). Functionally ventilation requirements had to adhere to an architectural concept requiring open panels to blend with surrounding closed panels (Figure 10 left). Conceptually this blending concept was modeled as an elastic string framework over the façade that could be “pulled” in certain areas where open panels were required. The elastic nature of this framework meant that the open angle dropped off the further a panel was from the open area. A further functional requirement was to avoid wind blown rain through panel openings around zones containing air handling units.

The control mechanism was implemented using a spreadsheet that served as a representation of the façade (Figure 10 right). Each cell represented a single cladding panel and contained a rotation value driven by a series of control cells. Control cells corresponded with panels located in front of air handling units, values in these cells were connected to all other cells in the elevation by a series of functions that modeled the required fall off in opening. Cells were conditionally formatted with colour fill to give a visual impression of the blending of panel openings.
Mechanical engineers provided detailed air venting requirements which were used to determine what set of rotational values were needed. The open area between panels was extracted from the model and mapped into a spreadsheet representing the façade. The total vented area over a plant room could be calculated and compared with the required area. The vertical dimension between panels was mapped into a third spreadsheet representing the façade. Individual cells were conditionally colour filled to visually flag façade areas where wind blown rain would be a problem (Figure 11 right).

In order to construct a solution for this problem an arbitrary configuration of rotation values was defined. The venting areas and wind driven gaps were simultaneously observed to ensure the correct areas were provided while minimising the possibility of wind driven rain. The three-dimensional model was checked to visually judge the smoothness of the transition from closed to open panels (Figure 11 left). Based on this evaluation the panel rotation values were modified in order to create an improved solution proposal. Once an attempt at improvement had been made the new model was again critiqued according to functional criteria, and rotation values modified, this was repeated until a satisfactory solution was reached.

It has been suggested [18] that in modifying a solution the designer must select a “focus or context”. In this exercise several foci were possible: 1. Achieve correct vent area for a specific plant room. 2. Achieve correct vent area for a block of neighbouring plant rooms. 3. Achieve satisfactory smoothing transitions between blocks of plant rooms. This sub process demonstrates the role of qualitative knowledge. In order to improve the solution it was necessary to develop an understanding of how the different outcomes are interconnected.

4.5. Fifth iteration – Information Issue

The final iteration in developing the parametric model for the cladding of Lansdowne Road involved the acquisition of knowledge relating to the tasks
of the cladding engineers, and the format of construction documentation needed to support this. This aspect of the design process was incorporated into the parametric model to enable design adjustment and instant update of construction data.

Contractually the cladding engineers provided a guarantee for the façade, they therefore needed to take responsibility for specifying manufacturing documentation. To achieve this they produced shop drawings and computer models of the façade components which the architectural design team checked. In order to do this they rebuilt the cladding geometry with their own software and incorporated their own details. The architectural design team was able to provide a written description of how to regenerate the geometry. However the cladding engineers requested the issue of geometric and numeric data extracted from the architects parametric model which was then used to rebuild the façade system.

The representational system devised for the façade ventilation design (one cell per panel spreadsheet) was adopted as the means to convey all numeric data required to configure brackets and panels. This included two angles to orientate brackets and the rotation angle. Additional data was required to configure tolerances on the double armed bracket; the cladding engineers required the horizontal and vertical angles that the rotation bar entered the support. Cladding manufacturers required rationalization of the 4000 varied panel lengths. The parametric model was adapted to group panels into preset ranges, 64 panel lengths were defined. In addition to numeric data three dimensional models were issued. These included centre lines of the rotation bars (Figure 12 right) and a pair of cross hairs, each locating the centre point of a component of the double arm bracket assembly (Figure 12 left). Three-dimensional geometry was used as a checking device by the cladding engineers.

This final phase of the model development process involved the capture of detailed knowledge from cladding design specialists. This knowledge was not available at the start of the parametric model development but gained in the later stages. In its final form the model is a representation of both design intent and construction method, understanding of which developed with the model. During the development the model provided a means for testing ideas and acquiring new knowledge while also the means of structuring the growing description of the problem space. As problem
description detail grew, the solution space decreased until eventually, a satisfactory solution was discovered. In June 2008 a full scale mock up of one façade bay was completed on site in Dublin (Figure 13).

5. CONCLUSIONS

The primary aim of this paper is to demonstrate how a parametric model can develop from an incomplete problem description through a process of knowledge acquisition. The cladding design task described here was an ill defined problem with an incomplete problem description, the goals and means were not fully established at the outset. Parametric modeling was the means of acquiring, capturing and representing the problem description as it developed. This demonstrates an alternative view to Burry’s [14] and Maher’s [15] need for everything to be considered at the outset for parametric model building.

Knowledge was acquired from two main sources, construction and development of parametric models and from experience of specialists working on the project. As the project progressed the amount of knowledge and therefore model complexity increased, while the solution space was reduced in size. A reduced solution space and well described problem can make finding satisfactory solutions more efficient, however other possible solutions may have been overlooked by the nature of the heuristic design process. Reconstructing the model to investigate alternative problem descriptions would be time consuming. The first iteration illustrates what Gero [19] has described as prototype instantiation through an initial specification of function, structure and behaviour, based on simple analysis of the problem. Using this starting point proposals were synthesised and evaluated in terms of the defined function and requirements. At this early stage this evaluation concerned construction practicalities and aesthetics. This acquired knowledge determined further functional requirements which demanded new computational knowledge. This case study did not begin by formal retrieval or recall of a similar project. However aspects of the methods used were based on ideas stemming from observed use and training in the software. Since this project other parametric design processes have been informed by methods developed and used here.
can be seen as the development of the memory of projects from which future design scenarios involving heuristics will draw on.

The second phase involved a reduction in the size of solution space by incorporating aspects of specialist knowledge into the function, structure and behaviour model. This type of knowledge would be described as context knowledge as it involves incorporating aspects that originate from outside. Here this involved material constraints defined by the selected manufacturers and financial constraints imposed on the project by the client.

The next phase illustrated how the model itself provides a way of developing knowledge. A behavioural system could be described and the function was known, what was required was the means of expressing this in an iterative computational algorithm to apply to the whole building. Various methods were proposed and evaluated to see if the functions were achieved. Once the computational knowledge had been acquired the model was used to generate alternatives, based on aesthetic and cost criteria one of the panel assemblies was selected.

The overall structure of the project can be clearly seen as embodying the propose-critique-modify model of design. This has been shown to develop knowledge of the problem. The facade ventilation task provides an explicit example of how this can be applied to find a solution when a problem is well defined.

Much of the reviewed design theory relating to knowledge in design originates from design theory in artificial intelligence. The aim of these theories is implementation in an automated system. The “design prototype” has been shown [26] to work using a well defined problem (a window design based around thermal comfort and light transmission). The same
conceptual methodology is used here to examine a more creative design task with ill structured problem description. It is proposed that this study demonstrates potential benefits in viewing parametric problems in terms of knowledge. Breaking parametric design problem descriptions into aspects of knowledge relating to function, structure and behaviour makes explicit what has formerly been implied. This can increase understanding of a specific task and reduce the complexity and additional time required to construct parametric models.

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