RAPID PROTOTYPING TECHNIQUES FOR BUILDING PROGRAM STUDY

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Abstract. This paper is original research that demonstrates new design possibilities for evaluation in the schematic phase of design through the use rapid prototyping as a tool of representation verses 2D drawing. These program shapes are created from CAD files using a three-dimensional printing and laser cutting CAM tools. This way of working is in response to two dimensional plan representation and evaluation (Mitchell 1976). This research combines the best of the visual aspects of plan representation and the formal representation of solid block modeling. The models in this paper demonstrate the building's physical scale of spaces, building use and overall form. Resulting models will demonstrate a new way of designing in CAD one that combined physical and visual ways or representation.

1. Introduction

1.1. DIGITAL FABRICATION

This paper is an original research in *Digital Fabrication* demonstrating design behavior when working with rapid devices in design. Resulting physical models demonstrate a new way to visually and physically explore designed space and form. There are three goals with this paper, (1) first is to define the behavior of digitally fabricating a physical model using two computer controlled devices and (2) to define the constraints of the process. Last will be (3) to use those constraints to outline a fabrication algorithm that will translate design descriptions in line form to physical description for phyical modeling (figure 1). The ultimate goal of the exploration will be to add to past generative work in design [Mitchell 1976] by presenting a method to generatively manufacture physical models from floor plan drawings.

Current works on *Digital Fabrication* refer to real scale physical fabrication where CAD information is used to drive large scale machines for final construction [Mitchell 2001]. This paper looks at *Digital Fabrication* in the design studio or office, where physical products are a fraction of the scale discussed by Mitchell.

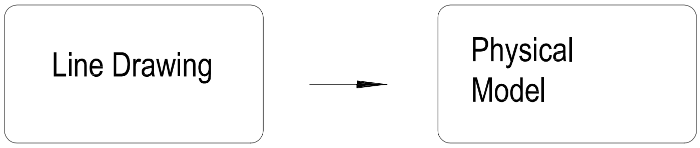

Figure 1. Digital Fabrication is part of the design process where a design description is translated into a physical representation using rapid prototyping devices.

Design models here are early stage representations within a professional design process known as design programming. Within this phase of the design process, practitioners explore the organization of the floor plan many times over in search of an optimized arrangement of spaces. An efficient plan is primarily based on the flow of people traffic through rooms. Efficiency is also based on adjacencies and a hierarchy of room use. These issues are visually evaluated by the designer once the drawing is completed, and each evaluation leads to the next representation for evaluation and re-editing. Typically the project moves on from programming design (phase I) to design development (phase II) only when a precise, efficient plan drawing is defined [Cuff 1991]. Paper drawings - either from CAD or hand drawn - are the traditional methods of building programs study where lines are shifted, trimmed and redrawn to create efficient plans. In CAD, spaces are represented parametrically as squares or rectangles on a page with a label identifying the use of each space (fig.1). These parametric rectangles represent an ultimate square footage for each rectangle, but they can be drawn in any relationship with another rectangle and length. Mitchell's paper creates these types of parametric descriptions generatively using algorithms that specifically create plans constrained by adjacencies of spaces [Mitchell 1976].

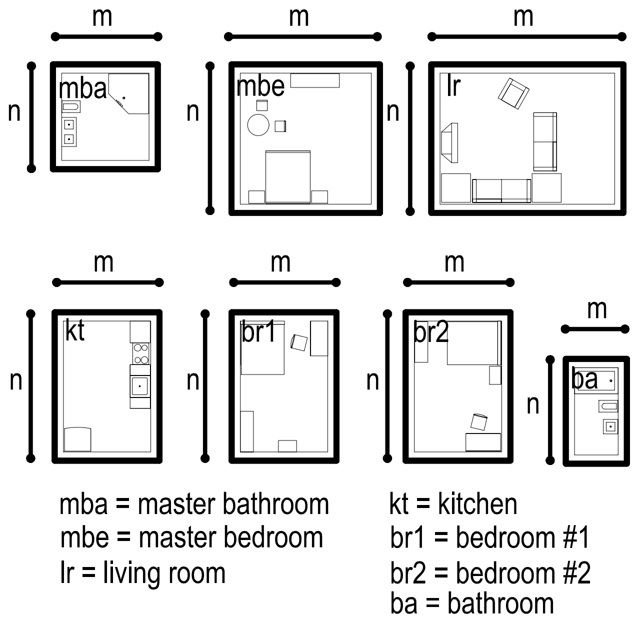

Figure 2. Parametric description of program plan elements with abbreviated labeling, each element is used to create a floor plan description.

1.2. PROGRAMMING DESIGN DESCRIPTIONS

Past papers that have studed plan programming in computation et al [Mitchell 1976; Stiny 1978a; Barbars 1980] presented various methods to generate floor plan drawings using rules to define a particular drawing style. These computer program theories generate many plans from which the designer will select an optimal floor plan diagrams, with wall, doors and windows. In particular, the Palladian Grammar is used to generate multiple plan drawings with window, doors and walls in the style of Palladio. Rules for shape and line placement are developed from an analysis of Palladio's plan drawings in the Four Books and some defined by Wittkower [Wittkower 1947]. The ultimate representation for evaluation is a plan drawing [Stiny 1978b].

Currently professional architects also use physical blocks (shapes cut from wood) labeled or painted to create models as a program description in three dimensions [Ragheb 2001]. These types of models have been made most famous by the office of Gehry partners. They provide an overall description of the buildings form and individual spaces or program elements in width, length and height. Gehry's office even uses scaled figures to help understand the size and span of a space in relationship to another space. The scale figures also help the designer and client understand the relationship of solid boxes (typically constructed of solid materials such as wood) and floor to floor heights.

1.3. DESIGN WITH COMPUTERS AND MANUFACTURING DEVICES

Both plans and blocks are limited in detail and understanding on the part of the client and at times the architect. The motivation of this paper is to combine the best parts of physical modeling with speed and ease floor plan drawing design. Digital fabrication affords many levels of design representation with the ease of shape transformation in CAD.

Digital Fabrication is the junction between design, computation and rapid prototyping, each field loaded with many overlapping interest and advanced possibilities. As a collective (design, rapid prototyping and computation) *Digital Fabrication* allows for the physical manufacturing of ideas using computers and machines that will some day transform the process of design on paper to design with physical products. The advantage of working with *Digital Fabrication* at the design scale is that building learning starts early opposed to learning during construction. Real building constraints are discovered before physical construction begins, and these constraints can be used as rules in a generative system. The results associated with construction constraints as part of the generative process reduce the number of random out put plans or models [Stiny 1978b].

There are three general goals with this exploration into *Digital Fabrication* at the studio level:

1. Define design behavior when working with design descriptions and computer controlled devices.

2. Outline an algorithm to handle the process of digital fabrication

3. Demonstrate a design possibilities using small scale models manufactured on digital devices

2. Design and Digital Fabrication Devices

2.1. DEVICE BEHAVIOR

There is a growing interest in the use of Rapid Prototyping Devices (RPD) in design practice and studio teaching. In the future, new models of practice will see laser cutters and building devices to constructing physical models in offices. Next contractors will manufacture building parts from CAD information for construction with information taken from the architect's models. The information used by the contractor will differ from the information used by the architect. Each uses different machines at different scales, creating physical representations with differing goals.

Digital information used to build a physical model on RPD differs dramatically from information used to generate line drawings or surface models used for computer renderings. Models fabricated on building devices (3D Printers) require simple descriptions typically in the form of parts for assembly by the fabricator. The descriptions of each object needs to be simple for machine production and re-editing after design evaluation. Simplifying design information and assembly design for the device are behavior constraints of the process.

Since the invention of the Stereolithography machine in the early 1980's, rapid prototyping devices (RPD) have been used by product designers to present a physical model to groups of evaluators for product review [Jacobs 1992]. Items such as electronic devices, shoes, or car parts are designed first with other mediums such as clay, or foam to define a shape. The clay shape is sculpted and altered many times before it is later translated into a CAD model either implicitly by modeling from measurements in the clay model or by 3D scanning. The rough CAD representation only outlines the overall shape of the object. The object is used as a shell from which other objects are built into or off of – such as buttons in the case of electronic models, where the shape is broken into a series of parts and assemblies. Last, CAD objects are manufactured on an RPD for display or physical testing by individuals or in groups. These models can also be working models such as cell phones or radios where the electronics are designed into the original CAD representation [Jacobs 1992]. In product design, there are typically a set number of physical explorations within the span of the design process; product designers typically create four or five models for design review.

2.2. MANUFACTURING THE DESIGN EXPLORATIONS

Architectural designers explore many descriptions of a design idea within the span of the design process. Three Dimensional print technologies and two dimensional laser cutting are designed for rapid manufacturing of information in any shape, in particular, at the early stages of design where the focus is on the overall presentation of an idea verses assemblies of parts and building scale construction descriptions. Models in this paper were manufactured from two devices - the laser cutter and a three dimensional (3D) printer both typically referred to here as rapid prototyping machines. Here each modeled instance comes complete with physical figures and furniture enclosed in a surrounding volume of colored acrylic sheets cut on a standard laser cutter. CAD models were created using a solid modeling program (AutoCAD r2002). The figures were created using a 3D character design program (Poser 5.0).

3. Descriptions

3.1. LINE AND PHYSICAL REPRESENTATION

For higher levels of visual evaluation in design, rapid prototyping is used to physically build program elements in detail (fig. 13). In addition to walls that help to define the form of each element, RPDs are used here to build furniture and characters in active positions. There are three types of CAD descriptions in each model: symbolic (furniture) descriptions, parametric models (characters) descriptions and solid models (floor and acrylic enclosure) descriptions that are transformed through Boolean operators. Each model in CAD must be transformed into a particular description for manufacturing on a particular device. For example CAM cutting (laser) does not need solid models to drive its cutting head along two axes; a 2D vector description will work well. All model components are designed and manufactured in three phases of design descriptions.

3.2. DESIGN DESCRIPTION

The first description is a design model, or modeling with no concern for fabrication. In this case the design description is contained in a bounding box representing walls, a floor plate and furniture. Each design description model represents a typical architectural setting for a particular space complete with 3D furniture and people. Objects in a design description are not fixed in place nor are they given methods of physical assembly. The model in figure 3b is an abstract representation of a bedroom built at a one to one scale. For fast design time furniture descriptions are 3D symbols are transformed for in the *xy* plane only.

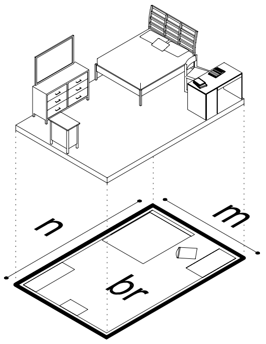

Figure 3. Two design descriptions created at a 1:1 scale for fabrication. The plan description is transformed to a three dimensional representation.

3.3. ASSEMBLY DESCRIPTION

The second description represents thinking in terms of materials, fabrication and assembly; in this case for 3D printing at a specific scale. Here assembly descriptions were substituted for design descriptions (fig. 4), and rules were applied define a specific materials manipulation and assembly. Model descriptions for walls represent 1/8" thick acrylic and a 1/4" in thick base built of 3D printed plaster. Tabs were added to the perimeter of the base in CAD and opposing cuts were made for the acrylic walls for a friction connection. Tabs 1/2" in length were used to join pieces of the acrylic top to each other. The tabs allow for fast assembly of walls to ceilings and walls to the 3D printed base. Assembly rules were applied independent of furniture, which is added later.

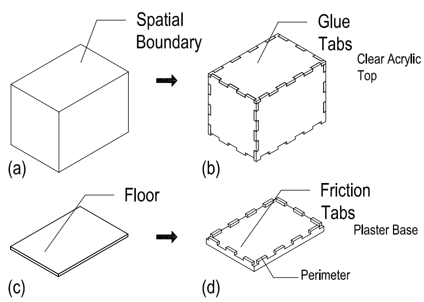

Figure 4. Rules of assembly

3.4. DEVICE DESCRIPTION

The third description is referred to as a device description where model parts are simplified into manufacturing parts for a specific RPD. Walls are flattened for laser cutting, and each wall or ceiling piece is arranged on a virtual sheet for fast cutting (figure 5d). Furniture is added to the transformed based (fig. 4) for accurate placement, then simplified by geometric reduction; for example the bed in figure 5a contains the full scope of details with numerous components and objects at real scale. This may seem large, but once scaled to one inch equals 8’ those same objects become quite small and difficult to 3D print. If the model were printed with all its detail most parts would break upon removal from the printer. To solve this problem areas of the model are built abstractly in the construction model (fig. 5b), and n this case parts were thickened.

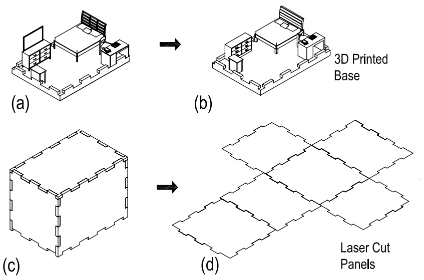

Figure 5.Device descriptions with thickened components (b) for printing; walls and floor translated to a flattened geometry for cutting (d).

3.5. PHYSICAL ASSEMBLY

The constructed model allows for handling of the base composed of very fragile parts. The plaster printed base is waxed for strength and the laser cut tops are glued and attached tightly to the base. There are few issues of tolerance between parts during assembly mostly because the modeled parts are small. The top and base are assembled by friction based assemblies.

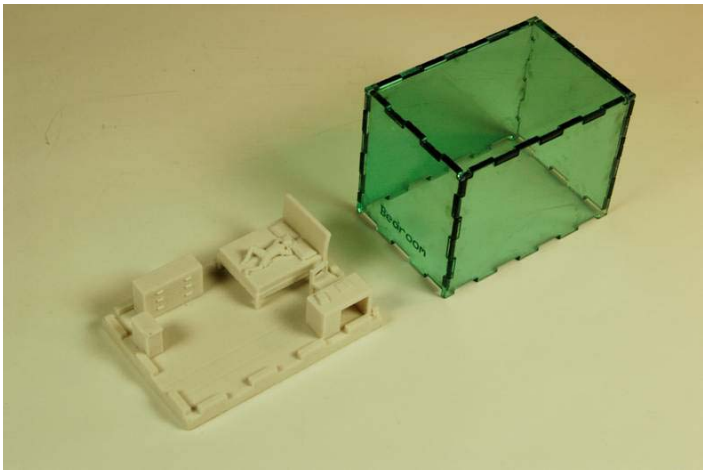

Figure 6. Final model fabricated from device descriptions using three dimensional printing and laser cutting. This model representation is called a Program Element

4. Fabricating Floors

4.1. WORKING WITH PROGRAM ELEMENTS

The resulting model in figure 6 is an example of one in a series of rooms that represent parts of a house. Each room is considered an *element* of a larger whole. Although the output of this one model is quick (approximately 2 hours to print, cut and assemble), fabricating many rooms of varying sizes can be extremely time consuming. The design process of using these program elements combines the goal of the wooden program block with a drawing. These blocks are visual methods to look at building form and understand adjacencies. However, each element can reflect a plan drawing and follow design rules of organization by stacking or moving blocks around while designing. For example one design goal (that does not consider fabrication) is that the bathrooms should always be next to bedrooms and should also be back to back with other bathrooms in order to conserve on piping for the plumbing stacks. The classic way to work with *program elements* would be to stack each element or align elements on one floor until an optimal arrangement of elements is found (fig. 7). Each arrangement is referred to as an instance. Each instance is evaluated visually and re-edited.

Design goals for element organization-quality are based on these issues:

1. Adjacencies of programmed spaces (horizontally & vertically)
2. Amount of non-programmed spaces – dead space
3. People flow from one space to the next

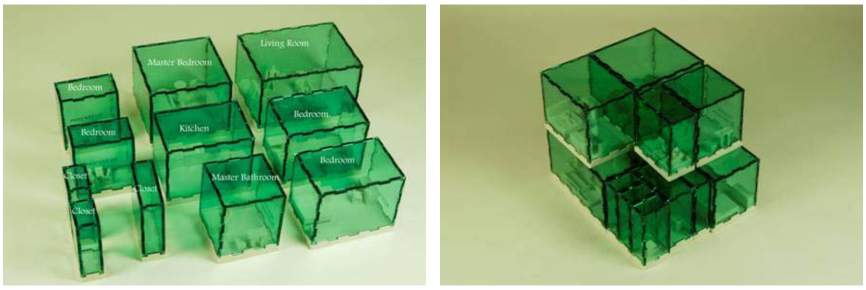

Figure 7. Program elements & program elements stacked

4.2. FLOOR PLATES MODELS

An optimal way to study sets of program elements is to place all spaces on one surface, here referred to as a *Floor Plate Model.* This is where program elements are combined in CAD then fabricated as one product verse the fabrications of many smaller elements. As a system of design, stacked program elements (fig. 7) are limited to those spaces that neatly fit next to another space. The process does not allow for editing of each element. This leads to arrangements with many dead spaces, poor adjacencies and low quality descriptions of a floor. The system must allow for each program space to be altered neatly. *Floor Plate Models* (fig. 8) are more desirable for qualitative evaluation than stacking program elements because they can include corridors that were not part of the pre-planned descriptions.

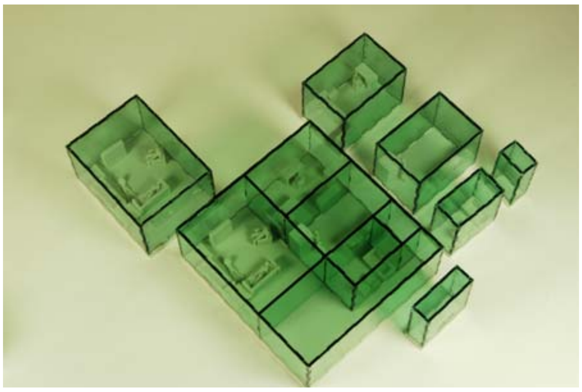

Figure 8. Floor Plate Model and Program Elements used to compose the larger model.

4.3. RULES FOR FABRICATION OF MULTIPLE ELEMENTS

The computational description of a *Floor Plate Model* is not just a combination of program elements. The model is also composed of non-rectangular rooms. Additional rules for fabrication are needed in order to construct a *Floor Plate Models*. First when two bounding boxes are joined in CAD they are a substitute for larger bounding boxes with a shared wall in this case an acrylic wall with connection tabs. The base is also substituted with a thicker based of that contains friction tabs at the perimeter. This is for all bases of any shape. The rules are listed below (fig. 9):

1. Perimeter Friction Tabs
2. Tabbed internal walls

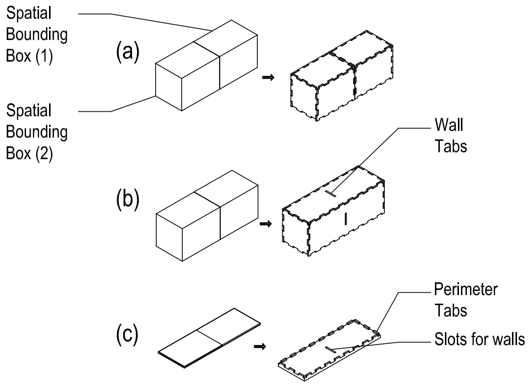

Figure 9. Additional rules for Floor Plate Model Assembly (a) typical condition of two bounding boxes, (b) tabbed internal acrylic walls (c) assembly rules for friction tabs.

5. Generative Fabrication

5.1. FABRICATION WORKFLOW

Now that the behavior has been established, a flow path is defined to support the digital fabrication process leading to an algorithm for fabrication. The process described here identifies the behavior of design when using digital fabrication to generate *Floor Plate Models*. From this behavior generative design programs such as those outlined by Mitchell can be combined with a fabrication algorithm to physically generate *Floor Plate Models*. Combining the two processes (digital fabrication and generative computation) will allow for two stages of evaluation. Although not completely necessary, the first stage is to evaluate the line drawing generated by the generative design engine before proceeding to digital fabrication. That there could be one process of design selection based on an evaluation of the plan drawing first. Once an optimal drawing has been selected, stage two is the application of fabrication rules to the plan drawing. Lines in the drawings are transformed through the three physical descriptions (fig. 10) to create a *Floor Plate Model*.

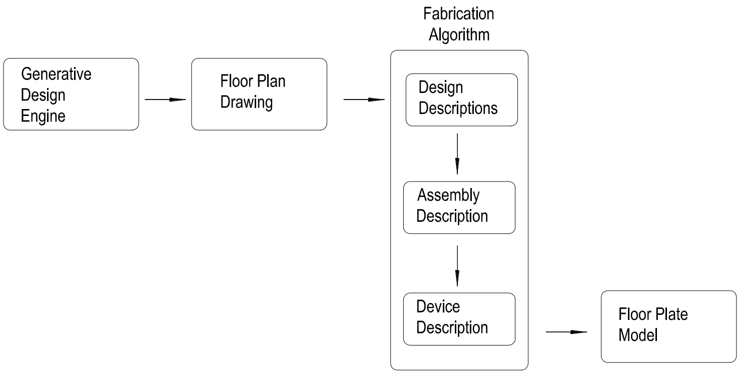

Figure 10. Digital fabrication workflow

5.2. GENERATING FLOOR PLATE MODELS

The Floor Plate Models in figures 11 & 12 are alternative design possibilities built from design descriptions in line form (fig. 11). These line descriptions are parametric representations of rooms within which are symbolic furniture descriptions. Boolean operatives are not used until the model is fabricated from the lines. Design Descriptions at the plan level are created by algorithms from work completed through a synthesis of rectangular floor plans (Mitchell 1976). In his paper, Mitchell identifies methods to create a line representation of possible floor plans whose constraints are based on adjacencies. Room sizes are based on proportions or specified wall lengths. His ultimate floor plan drawings are similar to the ones in this paper in figures 11. From this detail models are created and a scene that describes the spatial use is defined by characters and furniture placement. After the floor plan drawing is generated, each Floor Plate Model is translated and fabricated in 6 to 9 hours.

The first model represents rooms on the second floor of a three story house. This *Floor Plate Model* contains a central corridor and bedrooms arranged on opposing sides. It was built from the plan drawing in figure 11. This first design satisfies the goals for few dead spaces, associated adjacent spaces (bedrooms) and back to back toilets.

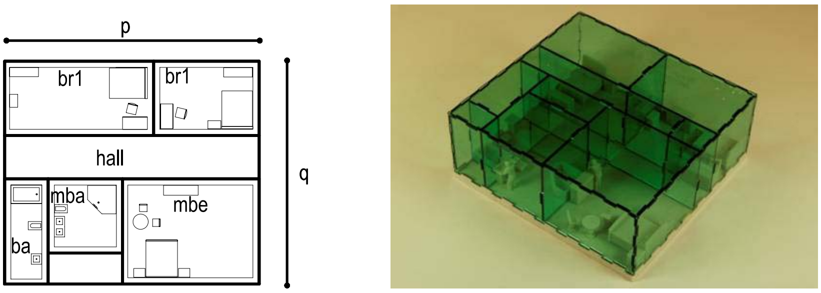

Figure 11. Plan drawing & Floor Plate Model created from the design description in figure 1b

The second model (fig. 12) is a U-shaped plan with bedrooms on opposing sides of a courtyard. The living room, kitchen and one bedroom are in one cluster. Also included is a dead area that could be transformed into a lounge. This model is less successful than the model in figure 11 because it contains a lot of dead space with a difficult flow pattern. A revised design goal for this was to reduce corridor space while maintaining a U-shaped plan. In terms of physical modeling, the base for design was very large and had to be manufactured in three sections then assembled.

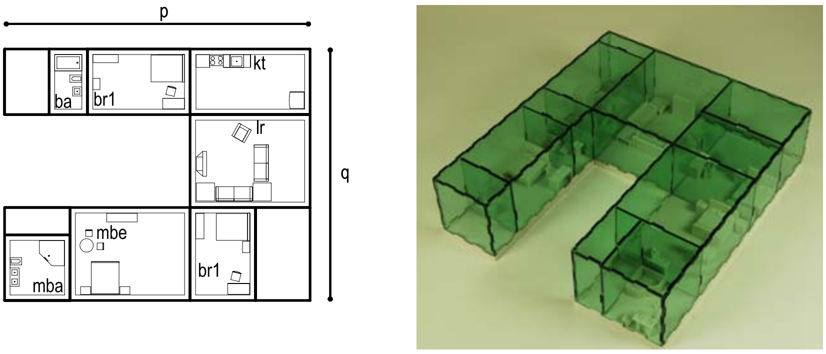

Figure 12. U-shaped floor plan drawing & Floor Plate Model created from the design description in figure 1b.

6. Conclusion

This paper defines design behavior when using digital fabrication in the design process. Final models were designed using a design generator and design rules, and physical models were manufactured from these plans and rules of fabrication. Constraints for the generative engines were defined by studying the process. Each physical model was built from a CAD file of parts, assembled and evaluated visually.

The visual goal of the *Floor Plate Models* is similar to the focused output of drawings in Mitchell's paper. These models allow evaluation to occur at the spatial level with out spending time on the details. It is the overall form and people flow through spaces that count most. These models are special studies, and do not address issues of style or function like fire stairs or window types. This method of model evaluation determines room patterns of use in many dimensions, not just the xy use but also qualitative values such as television watching, sleeping, bathrooms, etc.

This paper will lead to algorithms that can be used as part of an existing generative system. Most people have difficulties understanding floor plans, this way of working will open opportunities for lay people to participate in the design process. Finally working with rapid prototyping in the early stages of design also opens new possibilities for designers by making the process very visual and physical that will lead to undiscovered spatial relationship.

Figure 13. Detailed study of a person brushing teeth

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