THE RULE-BASED NATURE OF WOOD FRAME CONSTRUCTION OF THE YINGZAO FASHI AND THE ROLE OF VIRTUAL MODELLING IN UNDERSTANDING IT [1]

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ABSTRACT

The wood frame construction system of the Yingzao fashi is rule-based. In this system, the text can be understood as rules, construction as the execution of those rules, and the building as the output of the rules. To illustrate, we discuss a three-bay ting tang and some of the rules which govern its overall form and size. This three-bay ting tang is the smallest hall defined in the Yingzao fashi.

Virtual models offer a critical advantage over real models and drawings. This type of representation allows us to ask questions which are particularly relevant to the rule-based system. We can execute the rules quickly and thus concentrate on the rules, their output, and the relation between them. We propose some areas of research made possible with virtual modelling. One is a study of curvature as a product of several rules, including shengqi, cejiao, and juzhe.

INTRODUCTION

The wood frame construction system of the Song building manual Yingzao fashi is rule-based. By this we mean that the system defines a set of admissible buildings, but not by defining each member of the set individually. It defines instead a small set of rules which interact to generate the members of the larger set of buildings. The text, then, can be understood as the rules, construction as the execution of those rules, and the building as the final product of the rules.

When we interpret the construction system in this way, then the areas of greatest interest are the rules, the buildings, and the relation between them. What are the rules which generate the buildings? What buildings result from these rules? How do the rules determine these buildings and not others?

Virtual modelling offers us a valuable tool to investigate questions like these. Because it simplifies the task of copying and modifying components - executing the rules, in other words - it frees us to concentrate on the rules and the products in themselves. Is this important? Consider the alternatives: constructing a building or just a model is impractical.

Background

The present discussion of the wood frame construction system of the Yingzao fashi follows from the work of Liang Sicheng and Chen Mingda. Liang's achievement in respect of the Yingzao fashi was to make it comprehensible to the modern reader. To use his own metaphor, his Yingzao fashi zhu shi (1983) is a translation of the original text and drawings using modern language and graphic conventions. Chen's
contribution, in his *Yingzao fashi da muzuo zhidu yanjiu* (1981), was to state the rules explicitly and to resolve omissions and inconsistencies. He did this by studying the text and images of the *Yingzao fashi* on the one hand and field measurements of contemporary buildings on the other.

An example will make their accomplishments clear. The rule of *shengqi* (juan 5) states that the columns in a building vary in height, from taller at the corners to shorter at the central bay. Liang (1983, 260) illustrated the rule with the various elevations, from three to 13 bays, with the height differential as stated: three bays, two *cun*; five bays, four *cun*; seven bays, six *cun*; etc.

However, this use of the absolute unit *cun* is manifestly inconsistent in a work remarkable for its use of the modular unit *fen*. The only way to resolve this contradiction is to make the modular dimensions absolute. In the present system, this can be done only by specifying the grade (*deng*) or absolute value of the *fen*; dimensions in *fen* then have a value in *cun*.

This is precisely what Chen did (1981, 17-19). He studied both related passages in the *Yingzao fashi* and the column heights of extant buildings, and deduced that the dimensions given in the absolute unit *cun* applied to buildings of the sixth grade. Knowing the grade of the absolute dimensions, he was able to restate the rule in terms of the modular unit *fen*: the height differential is five *fen* for the first three bays of building width plus five *fen* for each two additional bays.[3]

We continue this line of thought by recognizing the rule-based nature of the construction system and proposing appropriate tools and areas of investigation.

A note on the examples

This paper is illustrated with images of virtual models constructed by our students using a virtual model kit. We developed the kit for teaching purposes, but it can also be used to pursue the kinds of research we suggest here. The system runs on the PC platform, using the Solid Modeler of AutoCAD Release 12 in Windows.

RULES AND PRODUCTS

Here we will illustrate the rule-based nature of the construction system by discussing a small selection of rules. We will show how these five individual instructions interact to define the approximate form and dimensions of a small building. We will not present an exhaustive catalogue of rules.

These five rules present a variety of aspects of the rule-based system. The first, which governs the building type, is crucial because it figures in the execution of many other rules. The second, which governs the grade, similarly figures in many rules, but is also dependent on the first. The third and fourth rules define what we call component-types, [4] in this case, the column and *lu dou*. These rules vary in their dependence on the first two, and also show touch on other aspects, such as grammatical combination. The fifth rule, *juzhe*, calculates the roof section from three parameters.

Building type

We begin with the rule governing the building type, because it offers a free choice. Unlike the other rules we will examine, the choice of building type is not dependent on any other factor. The *Yingzao fashi* alludes regularly to this distinction between *dian tang* and *ting tang* since, as we have pointed out, many rules are dependent on it. The column diameter in a *dian tang*, for example, ranges from 42 to 45 *fen*, while in a *ting tang*, it is 36 *fen* (juan 5).
The *Yingzao fashi* offers no written explanation of this obviously important distinction, but in *juan* 31 it does provide 22 sections: four of *dian tang* and 18 of *ting tang*. Primarily on the strength of these drawings, Chen (1981, 130-133) proposed a definition, which may be summarized as follows (see ill. 1).

The *dian tang* can be conceived of as two layers separated by the ceiling: the roof structure above, and the frame structure below, composed of columns of equal height and beams. Because these two layers are relatively independent of each other, the interior columns need not be located directly below the ends of the cross beams (*liang* or *fu*) in the roof structure. The *ting tang*, on the other hand, consists of repeated transverse frames (*liangjia*) which integrate columns and roof structure. The columns extend into the roof structure to support the ends of the cross beams and so are of different heights.

Chen's distinction is structural, but there are other aspects as well. In spatial terms, the most important distinction is in the ceiling: the *dian tang* has one, while the *ting tang* does not. Put in another way, the *dian tang* conceals the roof structure, while the *ting tang* leaves it exposed to the interior. In hierarchical terms, the *dian tang* is used for larger and more important buildings than the *ting tang*. [5]

**Grade**

The selection of the building type does not in itself define any actual components. Rather, it operates on other rules to limit their output. One such rule partially governs the grade (*deng*), or absolute value, of the modular units *cai* and *fen*, in which virtually all dimensions are defined. We will discuss the significance of these modular units presently.

The choice of grade is limited by the building type. According to the rule governing, the grade (*juan* 4), the *dian tang* requires higher (and larger) grades than the *ting tang*: first through fifth as opposed to third through sixth. The second limiting factor is the building width in bays (*jian*). Taken together, these two factors completely determine the grade. The first grade, for example, is used for nine- and 11-bay *dian tang*; the fourth, for three-bay *dian tang* and for five-bay *ting tang*; and the eighth, for ceiling coffers in small *dian tang* and for small pavilions. [7]

We return now to the modular units *cai* and *fen*, whose importance is clear from the first sentences on the wood frame (*juan* 4, all translations by us): "The cai is fundamental to all construction. It has eight grades, and is used to gauge the size of buildings." In keeping with this policy, virtually all dimensions are given in modular units. These definitions are prototypical, because to have an absolute value they require that the grade be specified. In other words, they are dependent on the grade.

**Column diameter**

Many of the rules in the *Yingzao fashi* define individual component-types. Take for example the rule defining the column diameter, which we mentioned above in our discussion of the building type. The column diameter is 42 to 45 *fen* in a *dian tang*, and 36 *fen* in a *ting tang*. This definition is typically prototypical in that it cannot be applied - we cannot construct an actual column - until the grade is specified and the absolute dimensions known. In other words, the rule defines the diameter of a *component-type*; to produce an *instance* of the component-type - with a diameter in absolute units - requires that the grade be applied. All rules which give modular dimensions therefore are dependent on the grade.

Notice that this rule is completely dependent on both the grade and the building type: these two factors together determine the column diameter. Thus, depending on the building type and the grade, the diameter of a column can range in absolute terms from a maximum of 864 mm to a minimum of 268.8 mm. [8]

*Lu dou*
Like the column diameter, the dimensions of the lu dou (cap block) are given in fen, but are independent of the building type (juan 4): "It is placed on the top of a column, and is 32 fen in both length and width. If it is placed on a corner column, then it is 36 fen [square]. It is 20 fen high." The size of the lu dou component-type is 32 fen x 32 fen x 20 fen high, and the size of an instance of a lu dou can range from a maximum of 614.4 mm x 614.4 mm x 384 mm high to a minimum of 307.2 mm x 307.2 mm x 192 mm high.

This rule dictates not only dimensions but also grammatical combination: the lu dou is placed on a column and not, for example, on a purlin. (For more on grammatical combination, see Mitchell 1990.) It is common for the definitions of component-types to prescribe which other component-types they may combine with and how. Another example is the hua gong (juan 4), which "interlocks with the nidao gong, and fits into the mouth of the lu dou" (see ill. 2).

**Roof section**

A more complex rule is that of juzhe (literally, 'raising and lowering' the roof, juan 5), which calculates the roof section. Juzhe is independent on three parameters: building type, building depth, and tile type. When the values of these parameters are known, the rule generates exactly one section; in order to change the roof section, one must change the values of the parameters. Nothing else affects the roof section.

The general procedure is to begin with the eaves purlins (liaoyan fang), whose positions determine the building depth. Next, locate the ridge purlin (ji tuan), or 'raise the roof' (ju wu), by calculating its elevation above the eaves purlins. Finally, locate each remaining purlin, or 'lower the roof' (zhe wu), in succession from the top down, by calculating its distance below a line connecting the previous purlin and the eaves purlin. (For a detailed explanation, see Liang, 1983, 265.)

**A three-bay ting tang**

We will now discuss how these five rules come into play in determining the overall shape and dimensions of a building (see ill. 3). As an example, we will examine a small three-bay ting tang, which is the smallest hall defined in the Yingzao fashi. A section of this hall is included as an example in juan 31. In order to carry out these rules, we will have to make assumptions about the values of some parameters; these are derived in ways that are by now familiar, so we will not explain them in detail.

1 **Building type:** ting tang

2 **Grade:** sixth
   This is determined by the building type and the building width (we assume three bays, small). At the sixth grade, 1 fen = 0.40 cun x 32 mm/cun = 12.8 mm.

3 **Column diameter:** 460.8 mm
   This is determined by the building type and the grade. In a ting tang, the column diameter is 36 fen. At the sixth grade, this equals 460.8 mm.

4 **Lu dou:** 409.6 mm x 409.6 mm x 256 mm high
   The lu dou is 32 fen x 32 fen x 20 fen high which, at the sixth grade, equals 409.6 mm x 409.6 mm x 256 mm high.

5 **Roof section**
   a Elevation of ridge purlin above eaves purlin: 217.8 fen = 2788 mm
   b Elevation of mid-purlin above eaves purlin: 97.0 fen = 1242 mm
   These elevations are determined by the building type, the building depth (we assume 660 fen = 8448 mm), and the tile type (we assume "flat" tiles, ban wa).

We have now demonstrated the rule-based nature of wood frame construction of the Yingzao fashi. We examined five rules, and showed that they are stated individually, but contribute collectively to the approximate form and dimensions of a building.
VIRTUAL MODELLING AND THE RULE-BASED CONSTRUCTION SYSTEM

When we understand this construction system as rule-based, then we are interested most in the rules, the buildings defined by those rules, and the relation between the two. In more concrete terms, what are the rules of the Yingzao fashi, and how are they stated? What buildings does the text implicitly sanction; what buildings does it forbid? How do the rules accomplish this?

As we have discussed, Chen (1981) restated the rules explicitly and consistently. We thus focus our attention on the buildings as output generated by the rules. What is the output, and where does it come from? In more traditional historical terms, what are our sources? Here we will discuss three types of output - real buildings, real models, and drawings - and their limitations. We will then consider the advantages of virtual modelling vis-à-vis the Yingzao fashi and propose appropriate areas of investigation.

Real buildings

Real, extant buildings are the obvious point of departure for the study of wood frame construction according to the Yingzao fashi. Liang and Chen used this source in their work. Real buildings have the advantage of being real: they were built and so reflect the reality of contemporary architectural practice.

On the other hand, there are two problems. First, there are few extant buildings from this period. Chen (1992) lists only 47 wood frame buildings from the Tang, Song, and Yuan. Second, and more serious for the study of a rule-based system, we cannot assume that these buildings followed the rules. In fact, both Liang and Chen showed that, while they accorded broadly with the manual, they varied in their details. As Liang (1984, 88) wrote of the Sanqing dian of Xuan Miaoguan in Suzhou: "Although it was built in 1170, not even three-quarters of a century after the Ying-tsao fa-shih, it has lost much of the vigor of that time and appears much more ornate than contemporary and even later structures in the north." The buildings on Chen's list span large distances in time (almost 500 years) and space (Shanxi to Jiangsu), so we must expect deviation from the rules.

Real models

Real models, say of wood, offer the advantage over real buildings that they can be built as exact products of the rules. This makes it possible to experiment with different values of parameters to see the effect on the final output. The problem with real models is not theoretical, but pragmatic: they require extravagant time and effort. Each component in a model must be made separately. To make a model with hundreds or thousands of components is too impractical to contemplate; comparison models are even more farfetched. More important, because the work of executing the rules is so overwhelming, it obscures the issue at hand, namely the relation between the rules and their outputs.

Drawings

Drawings are less labour-intensive than models, but they show less information: they are two-dimensional. Some of the most interesting rules in the Yingzao fashi have clear three-dimensional implications, such as those governing curvature. The roof, for example, is curved in three dimensions simultaneously; drawings cannot convey the totality of this effect.

Virtual models
Virtual modelling, by which we mean the use of three-dimensional computer models, offer two important advantages in the study of the rule-based wood frame construction system. First, virtual modelling allows us to construct models precisely according to the rules. This makes it possible for us to study the relation between the rules and the buildings they define.

Second, it is easy to make virtual models, that is, to execute the rules. This is because both virtual modelling and the rule-based system share the distinction between primitive and instance. The Yingzao fashi requires large-scale repetition; in virtual modelling there is no simpler task. This is the opposite of real modelling, which contradicts this conceptual distinction. In this way, the easy construction of virtual models enhances the relation between the rules and their output. Our students, for example, constructed 16 models in four weeks. Construction is so easy, in fact, that they voluntarily did comparison studies. Comparison study is an important way of studying a rule-based system, which employs parameters with variable values.

Naturally, virtual modelling has its disadvantages. In our teaching experience (Li and Tsou 1994, 1995), we have found three, all tractable. First, there is no gravity: structurally implausible buildings do not collapse. Second, impossible connections are possible: two components can occupy the same space at the same time. Both types of mistake are impossible with real models. Third, the operation and manipulation of virtual models can be tedious. We have been addressing this problem by customizing the interface for the operations required in this construction system. These shortcomings notwithstanding, for the study of the rule-based construction system of the Yingzao fashi, virtual modelling offers important possibilities simply unavailable in any other medium.

Possible areas of investigation

**Representation of knowledge in the Yingzao fashi**

We propose several areas of investigation using virtual modelling. The first is to attempt to represent its embedded knowledge by articulating rules and then executing them. Such an approach clarifies the relation between rules and products.

This method has been used to study the architecture of Palladio (Stiny and Mitchell 1978, Hersey and Freedman 1992). Compared to the Yingzao fashi and its built and drawn products, Palladio's rules are less explicit, but his products, springing from a single mind, presumably reflect those rules more faithfully. Such an approach to the text at hand would similarly close the gap between rules and products. We envision two possible studies:

1 *The set of sanctioned buildings*. Generating the set of sanctioned buildings - and, for that matter, those not sanctioned (see ill. 4) - would provide a basis for understanding the "architectural style" of that manual. Comparing these models with extant buildings would illuminate stylistic development toward and away from the Yingzao fashi. To refer again to the Sanqing dian of Xuanmiao guan in Suzhou: what would it look like if it followed the rules?

2 *The rules of curvature*. There are at least three parameters which introduce curvature to the otherwise orthogonal wood frame: *shengqi*, *cejiao*, and *juzhe*. We can study the effect of each parameter by varying it independently to construct sets of comparative models.

As a simple example, we show a single three-bay *ting tang* in four variations: with *shengqi*, with *cejiao*, with both, and with neither (see ill. 5). This little study suggests that *shengqi* and *cejiao* have very different effects on the appearance of the building, at least at the scale shown and in the two-dimensional representations of the monitor and the printout. This line can be pursued by introducing different degrees of *shengqi* and *cejiao* and other parameters such as *juzhe*. Such a study might contribute to our understanding of their role as structural or visual devices.
Structural analysis

Conventional methods of analysis of wood frame structure in the *Yingzao fashi* are complex and limited (Wang 1992). Computer-aided structural simulation and analysis of virtual models would contribution to our understanding in this area. How, for example, does the prescribed wood frame resist wind loading? Comparative studies would further enhance this type of investigation.

CONCLUSION

We have now shown how virtual modelling compares to traditional sources in the study of the *Yingzao fashi*. It offers both practical and theoretical advantages: it makes construction easy, and it embodies the primitive-instance distinction, which is the essence of the rule-based system. We have proposed several lines of investigation which exploit this felicitous correspondence between tool and substance.

NOTES

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3 At the sixth grade, 1 fen = 0.4 cun. Thus two cun at the sixth grade means five fen; the grade need not be specified.

4 We use the term component-type to refer to prototypical components, or primitives. These should be distinguished from actual components, or instances. The difference will be made clear in the discussion about the rule governing the column diameter.

5 *Dian tang* and *ting tang* have been translated as high- and lower-ranking halls, respectively, presumably because of the hierarchical distinction (Steinhardt 1984).

6 The *cai* and the *fen* are both modular. The *cai* is a two-dimensional unit 15 fen high and 10 fen wide. Because it encompasses both horizontal and vertical dimensions, the *cai* can be ambiguous; we will use *fen* exclusively.

7 At the first grade, 1 fen = 0.60 cun = 19.2 mm; at the fourth, 1 fen = 0.48 cun = 15.4 mm; and at the eighth, 1 fen = 0.30 cun = 9.6 mm.

8 The column diameter in a first-grade *dian tang* is 45 fen x 19.2 mm/fen = 864 mm; in a sixth-grade *ting tang*, it is 21 fen x 12.8 mm/fen = 268.8 mm.

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