months to complete and install our part of the work. The whole floor, all two acres of marble and all 400,000 pieces, had to be completely laid, ground, and polished in two months.

We were thus facing, in microcosm, the massive problem which has persistently faced large-scale construction in the modern era. Because of labor rates and time pressure, construction has to move in very large volumes and at a massive rate, otherwise it becomes too costly in time and money. During the 20th century, as a result of these conditions, work was typically crude, governed only by the capacity to go fast and cheap — and this led to the devastating loss of personal quality and of local order and adaptation which the four books of THE NATURE OF ORDER are all about.

The question is, under our modern conditions where labor rates *are* high, and where the need for speed *is* pressing: Can we hold cost constant and yet construct large works in a way which is profound, personal, detailed, and loving — yet still respectful of these necessary conditions that are nowadays imposed by the modern era?

4 / THE CORE OF THE SOLUTION: A COMBINATION OF LARGE NUMBERS, HIGH SPEED, MINUTE ADAPTATIONS, CRAFT, AND COST CONTROL

A beautiful floor from the basilica of San Clemente in Rome, made about 12th century. The apparent roughness of this floor is far from random; its roughness is necessary to achieve the coherence and complexity of the overlapping figures in the design. In principle, such a floor design CANNOT, IN PRINCIPLE, be made well from modular components.

In conventional late-20th-century methods, a problem of this kind was typically solved by using mass-production components and trying to get variety and complexity by random arrangement and combination of these mass-produced components. However, this sort of technique, though it did occasionally create an impression of something lavish, was not able to capture the stunning beauty of the medieval floors, simply because that beauty relied on inch-by-inch variation and adaptation — with the result that every stone felt just exactly *right*. An example of the true beauty of the ancient floors, showing its reliance on subtle adaptation, is shown opposite, in a 12th-century stone floor from Rome. The idea that one could create a comparable level of beauty in a high-technology environment had simply not been tried in modern times. But, using living process, the problem can be solved.

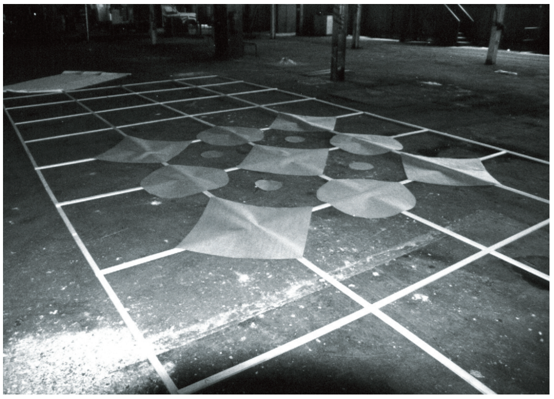
The solution to the problem is an interlocked pattern of action in which we use resources for speed and efficiency, allowing them to perform what they can perform, rapidly and cheaply, yet interleaving with them, smoothly and cunningly, the personal qualities and procedures needed to create genuine fine-scale adaptation. In addition, there must be a set of procedures where (using electronic means, computers, and a variety of sophisticated but apparently naive simulations) one is able, at high speed and in very short time span, to make just those kinds of detailed artistic adaptations which were possible in the 12th century, but in a new (and now partially simulated) form which can be transmitted to the real project through high-speed electronic means. The two procedures — the fast of the modern and the slow of the old — are united to form a new kind of process, one which would have been unrecognizable in the 12th century and unrecognizable in the 20th century. It is something, in principle genuinely new.

To describe what had to be done and how we arranged to do it, I start with some statistics for the floors. The total area to be covered was about 8,000 m^2. In making an assessment of the overall statistics of the design, number of pieces, and cost of fabrication, we made a small sample about 18 inches square (shown on page 571). This sample, containing 116 pieces in 50 cm by 50 cm (464/m^2), was imagined in part as a 1:5 scale model of a larger area and in part as a 1:1 full size model of certain more detailed areas. On average this model suggested an overall statistic of about 50 pieces per square meter, the pieces having a mean diameter of 15 cm, and mean edge length of 60 cm, requiring a total length of 30 meters of cuts needed for every square meter of floor. This gave the project as a whole about 400,000 pieces for the 8000 square meters of floor, with a total length of cuts that would have to be made of 240 kilometers.

Let us consider the design and production aspects of this enormous task. Just the pure production *alone* is a huge task because of the need for colossal speed that OMMA required. The 400,000 pieces had to be laid and polished in two months. One might judge that only mass production could hope to manage the huge number of pieces which have to be cut and installed under such a time constraint. This reflects the general pressure that used to be felt throughout the 20th century as builders asked themselves how they could build — fast enough — the offices, roads, airports, houses, furnishings, windows that were needed all over the world to meet the needs of 6,000,000,000 people in the world. The Athens floor is a microcosm of the massive production problem we face daily in the modern world of building.

5 / ADAPTIVE DESIGN EMERGING WITHIN THE WHOLE

But beyond the need to cope with production and speed, there is a far more complex problem: the scale and complexity of the design problem itself, and of the needed adaptations to reach harmony. This is the massive design aspect to the whole thing: the desire to make a living unity. In this respect, too, the Athens floor is a microcosm of the entire world of building. We know buildings are better when made with love and care and time and patience. But in the world of mass production, high labor rates alone seem to make it impossible, so we have come to accept the steril-



A mockup in our warehouse. This design, one of many, was first inspired by sketches like the one on page 570. However, it was not designed or calculated in advance but rather worked out by tearing and cutting pieces of paper, at full size, in response to what looked good on the warehouse floor. In particular, it was motivated by the search for what designs and arrangements seemed to create a profound relationship between a person standing there and the place.

Black and red mockup of another floor design, worked out by eye on the floor of another warehouse

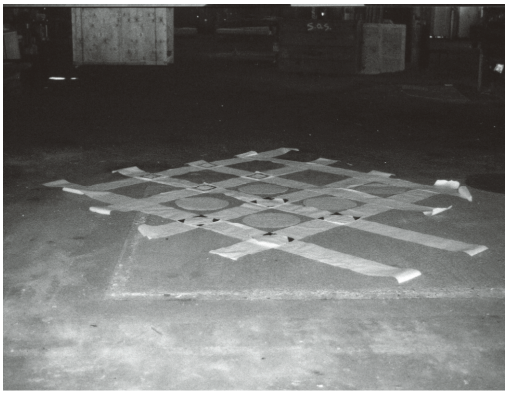
ity of mass production as an inevitable result of the modern era. Yet we are wrong to have done so; the argument of these four books makes that thoroughly clear. And in the Athens floor, too, it seems that a mass-production approach to these floors would deny their very purpose — which was the client's expressed wish to create something with the same depth and beauty as was encountered in the 12th-century Italian church floors. That can only come from time and love and patience.

If a man can cut one piece of marble in five minutes (a very short estimate for the average), he could cut 12 per hour, or about 100 pieces per day. This one man would take 4000 days, eleven years, to cut the pieces for the Athens floor. Of course, you will say that we can use an army of marble cutters, twenty, let us say, so that we may cut the pieces in half a year. But the moment we visualize that, we have to imagine not craftsmen, but *workers*, slave-like worker ants blindly cutting as fast as they can go. And, anyway, the artistic skill to make a beautiful floor does not even exist any longer in that environment. Only the technical cutting and laying skills remain.

So in our epoch, we have come to imagine a floor which is designed in an office and where the pieces of the design worked out on the drawing table are transferred to the hands of the twenty worker-ants who will cut exactly according to the blueprint, and their counterparts among the floor layers who will lay the floor exactly as it shows on the blueprints.

It is a fantasy, of course, to imagine that something beautiful can be made this way. This whole approach is a disaster. It cannot create life or harmony.

So here we have run into a very big problem — not in cutting, but in the design process itself, as it relates to high speed craft and production. It is a fact, repeatedly verified by experience, that the feeling of such a floor cannot be accurately judged from a drawing made in advance. In order to understand what looks right, feels right, is right on the floor, one can only judge by actually drawing on the floor, by changing and modifying the pieces and their shape and color, while one actually makes the floor. Scale, above all, is vital. The exact size of pieces matters and the right size only becomes clear when one is standing looking down at them. And, for a repetitive pattern, the way it looks at an angle as it disappears makes a sharp difference. Even twenty or thirty feet from where you are standing, what works and does not work are obvi-



An earlier stage, when strips are first being laid out to get the gist of a successful configuration on the floor

Another configuration laid out, by eye, on the warehouse floor

ous — *but entirely different from what one might have predicted on a drawing board sketch.*

For this reason, as I told our client, it would be necessary to work out the whole design on the ground while looking at it in a real context. And further, one can only do such a huge thing bit by bit. One's emotional and mental concentration cannot simply take in two acres of 400,000 pieces as one design. I estimated (working, for the sake of argument, on one hundred separate sections and doing one section every two weeks) that it would take a year merely to *design* the floor.

Even the simple-looking marble panel shown on page 571, represented the effort of four people working for nearly two weeks making different versions, sketches, mockups, adjusting them, trying them. It seems a lot of time to take, but the effort shows in the result. The final product is a harmonious thing.

The problem is, then, how such a slow process can be fit together with some kind of ultra-fast process, to produce results fast enough and efficient enough to be sensible in today's world, and do-able at a reasonable price?

6 / THE WATER-JET CUTTER

In order to make the creation of the floor feasible at reasonable cost and in reasonable time, we decided to use an extraordinary instrument. This instrument, invented less than ten years ago, is a very thin jet of water, about 1/16th inch wide, at enormously high pressure. The pump operates at 60,000 psi. In some cases a small quantity of very fine silica dust is added to the water jet, increasing its cutting power.

Amazingly, a water jet of this type can easily cut a three-inch solid stainless steel plate at about the speed a bread knife moves through bread. It cuts marble sheets easily and at high speed, with great precision and control. The cutting head is controlled by computer instructions originating in a CAD drawing and is automated to cut configurations of almost any size and complexity.

A computer-controlled water-jet cutter in Germany

Cutting a piece of marble with a 60,000 psi water jet

Using water jet cutters, we will be able to cut the pieces of the Megaron floor at reasonable cost and in a reasonable time. Using three machines in continuous operation, the 400,000 marble pieces and their 240 kilometers of edge length to be cut, can be cut in about six months. This is to be compared with eleven years of cutting time needed for a single craftsman using conventional masonry saws) to cut the same marble pieces.

Additional facts in favor of water-jet cutting are the following:

Dust-free cutting
No thermal stress on materials
High flexibility thanks to integration of water jet into two- or multi-axis guide systems
Little swarf due to narrow width of cut
Minimum reaction forces
Minimum mechanical stress on material
No deformation of material surface
Commencement of cutting at any point
No need to start cuts at the edge of marble sheet

Ability to transfer a complex computer drawing directly into a cutting operation, without any intermediate process.

7 / PREFABRICATION OF MARBLE ON FIBERGLASS MATS FOLLOWED BY ON-SITE MODIFICATION AND CONTEXT-DETERMINED DESIGN ADJUSTMENT

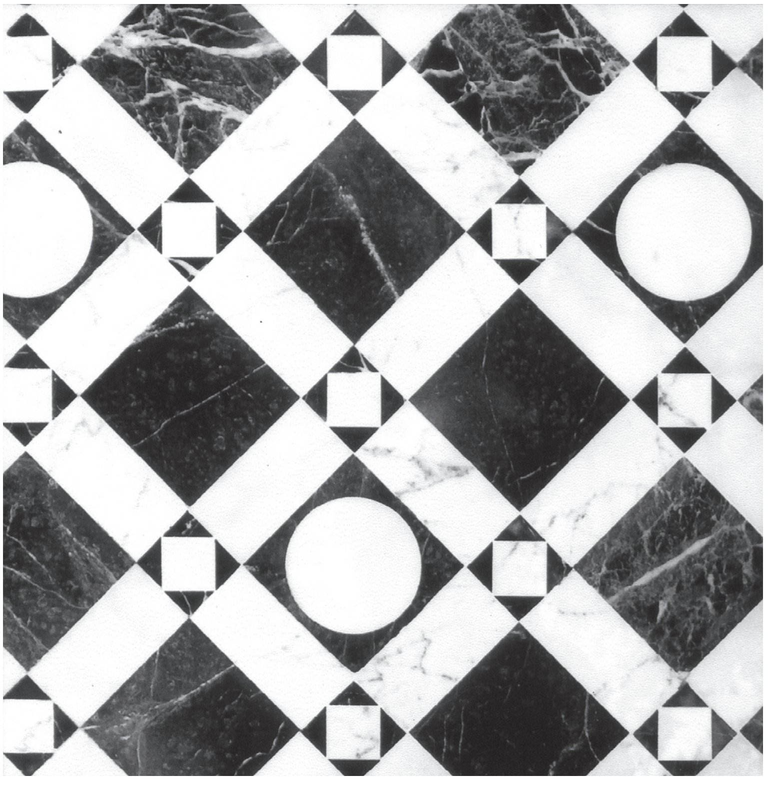
The next question concerns assembly: the process of laying the marble. As mentioned, in this particular case, the industrial and production conditions of the job required that it be laid in two months, and that our access to the slabs could be no more than two months.

Since the character of the floor, its design, its beauty, and its subtlety, require a long time for looking at the floor, pondering its effect, possibly modifying pieces or small portions of the design, it was clear from the outset that this could not be done in situ on the actual site itself.

On the other hand, for other reasons already given, it was also clear that we could not expect to have success by making drawings at a drawing board and working from them.

We therefore decided to do the next phase of work — the on-site adjustments — in California, not too far from our offices, where we could have daily or weekly access over a period of six to twelve months. We arranged to have a large warehouse area, larger than any one segment of the Athens floor, in Watsonville, California, near the shop of our water jet cutter.

We divided the 8000 m^2 floor into about one hundred sections, each section typically about 100 m^2 (1000 square feet) in area, and each section with its own adjustment process. These sec-



A small piece of a floor, in black, white and green marble, sketched and designed by the full-size mockup techniques described on pages 566–70. This sample is about 18 inches by 18 inches, contains 100 pieces, the smallest less than an inch across. It was laid out in CAD from our rough sketches, then cut and fabricated in about an hour. Christopher Alexander, Randy Schmidt, Demetrius Gonzalez, and Larry Berk, 2001.

tions were made roughly on the basis of work on a 1:50 model of the whole project. As each section became sufficiently well-defined, detailed design could then take place on the warehouse floor, allowing the opportunity to shape form, color, and size of pieces so that they make sense emotionally, and so that the right amounts of adaptation and variation occur naturally. As each section is finished as a full-scale design made in paper on the warehouse floor, its pieces are then transformed into CAD, and made ready for cutting.

The segment of 100 m^2 was itself divided into about a hundred smaller sections, each about two feet by four feet. Each of these two-foot by four-foot sections would be assembled on a fiberglass mat, the marble pieces being glued with epoxy to the mat. Each mat, then, about two feet by four feet, would hold, on average, about 50–100 pieces of marble, some large, some tiny. Each such mat weighed about 20 lbs, fairly easy to lift. The mats for each section of the floor would be shipped to Athens in a container and carefully numbered and laid on the floor where they were to go.

Before shipping, the roughly one hundred fiberglass mats, with marble pieces cut, placed and glued, were first to be laid together in the warehouse floor which was our staging area and experimental "adaptation zone." While the floor was in this preliminary demountable form, various adjustments were to be made, including larger scale adjustments where feedback from the full-size floor told us that certain pieces of color should be modified to increase the harmony of the whole. They also included small-scale adaptations in which individual pieces could be modified until everything fit together better, aesthetically.

Whatever changes were needed would then be made on the mats, and the mats for that section would then, finally, be made ready for final shipment to Athens. Transportation cost from California to Athens was relatively small and played little role in overall cost.

But here again, the danger inherent in mass production reared its head. If the production of the mats was too mechanical (even though the design, as first cut, was based on real world experiment on the floor of the warehouse, and done in paper) there remained the possibility that design, dimension, dark and light, any number of things — might be not quite right.

In a traditional process, because it was going so slowly, there was always plenty of time to adapt to discoveries that there was too much of one color, or that one of the pieces or designs was too big, or that the border was too dark.

In our more highly mechanized process, this aspect of living process had to be accommodated. So, as the mats were cut and glued, one by one, they would be laid out together, in position, in our warehouse, always coming as close as possible to the design and the reality of the finished floor. The moment we saw problems developing, we could jump in and make corrections — changing the design, the color of the material, the relative proportion of field and border, the relative frequency of animals or geometric elements, the appearance of large figures in the floor as one begins to see large extended areas.

In performing such a task, as the floor of each section is being cut one has to watch carefully how it is going, always keeping an eye on the whole. All needed corrections, adaptations, improvements, changes, could then be communicated directly to the cutter, and the final modified mats could then be prepared.

Final adjustments — borders, for example, to take up the dimensional slack of the design — could be cut on site after they are in position on the final floor in Athens itself. This provides the last level of adaptation in the building, but is a level of work consistent with the high-pressure installation schedule.