Proceedings of Symposium on Mosque Architecture, Vol. 1B, pp1-16, College of Architecture & Planning, King Saud University (1419H-1999)

Planning and Control Procedures in the Construction of the Sliding Domes of the Prophet's Holy Mosque in Madinah, KSA

Khalid A. H. Taher
Civil Engineering Department, College of Engineering, King Saud University
Riyadh, Saudi Arabia

Fuad A. Rihani
Saudi Binladin Group
Jeddah, Saudi Arabia

Mahmud Rasch
Sonderkonstruktionen und Leichtbau GmbH,
Leinfelden-Oberaichen, Germany

Benet M. Kaser
Buro Happold
Riyadh, Saudi Arabia

Abstract: The King Fahd extension of the Prophet's Holy Mosque in Madinah, Saudi Arabia, is the largest and most complex addition in the Mosque's history. One of the most innovative features in this landmark project remains to be the unique twenty seven sliding domes, 18m x 18m each, covering its twenty seven interior open courtyards. With complex geometric and quality requirements, the design and construction of most components and segments of these domes had to rely on state-of-the-art computer technology. The project represents a real-life example of advanced planning, scheduling and control procedures. Such procedures have made it possible for the complex design and construction of the Sliding Domes to be completed in a successful, economic and timely manner. This paper describes the Sliding Domes project, its design and its construction constraints. It also describes in detail the processes used in planning, scheduling and control. The paper introduces the use of a driver-based management technique and how a prototype-assisted communication system were utilized in the planning and control of this project. The successful completion of these magnificent domes is a witness to the validity and practicality of the use of such practices in advanced projects.

Introduction

The first decision in conventional strategic planning is the selection of the best project for implementation or, given a specific project, whether or not to pursue it. In most cases, a decision on project selection or implementation is a balance between strategic goals and the associated risks. In the absence of a strategic driver, risk minimization becomes the guiding principle for project management. [1] In the majority of cases, the cost of a project is the risk factor used to reach that decision.

In the Sliding Domes project, as with other large projects, strategic drivers were coupled with the identified risk factors to form the project's planning and control systems. The basic obligation to succeed in this one-of-a kind project was the main strategic driver for all project participants. The strict quality standards formed the essential and leading source of risk in this project. Time was a dominant factor and it has added another dimension to this risk.

The Sliding Domes project contained the following risk factors:

- quality standards for the Domes' construction and installation and for its ornaments were strict;
- characterization of the quality of the raw material were subjective;
- communication with the suppliers and manufacturers was difficult;
- degree of familiarity of some subcontractors (especially the ornamentation artists) with the construction constraints was inadequate;
- site access was restricted.

Conventionally, different measures for project control are used at different stages of a project. At the outset, projects are normally defined in terms of their contribution or profit, approval for expenditure is characterized by cost and schedule, implementation by resources and deliverables, and so on. The use of a single project planning and control measure that streamlines the control process and facilitates planning, can help team-building and communication. Many others have suggested the use of a single measure for planning and control.[2]

The Sliding Domes project was modeled as a parallel system of conventional projects, where each project was focused on a single dome with common life-cycle operating requirements.

This paper describes the Sliding Domes project, its design and its construction constraints. It also describes in detail the processes used in planning, scheduling and control. The paper describes a conceptual frame work for 'driver-based management', a concept that was used for the planning and execution of this project. The concept is based on concurrently maintaining strategic and risk views of the project during the planning and execution stages. The concept uses a Work Breakdown Structure that is focused on deliverables. The deliverable in this project were the timely delivery of components at the required quality, and the timely erection at the required specification. The process has been validated by virtue of the success of this project.

The Prophet's Holy Mosque and the Sliding Domes

The Prophet's Holy Mosque in Madinah, the second holiest site in Islam, consists of the existing old part of the Mosque, about 16,500 square meters in area, and the new King Fahd Extension of 82,000 square meters. The new extension includes twenty-seven inner open courtyards, each 18m x 18m, which required a mobile cover that could be opened and closed to control and support the air-conditioned environment of the Mosque. This resulted in the design and construction of twenty seven sliding domes, Figure 1. The sliding dome consists of a spherical portion and a support frame riding on four steel wheels on steel rails. Each wheel is driven by a direct-drive electric motor with a manual over-ride. The spherical portion of the dome consists of the following elements, Figure 2:

1. a steel structure composed of 24 meridians and 3 ring beams. The structure supports the inner and outer cladding in addition to internal insulation and waterproofing systems;
2. an inner cladding of wood-laminate reinforced by wood-laminate flanges and supporting the intricate decorative elements;
3. an outer cladding of 50 mm hexagonal ceramic tiles glued with epoxy resin to carbonfibre laminate which in turn is reinforced with carbon-fibre flanges.

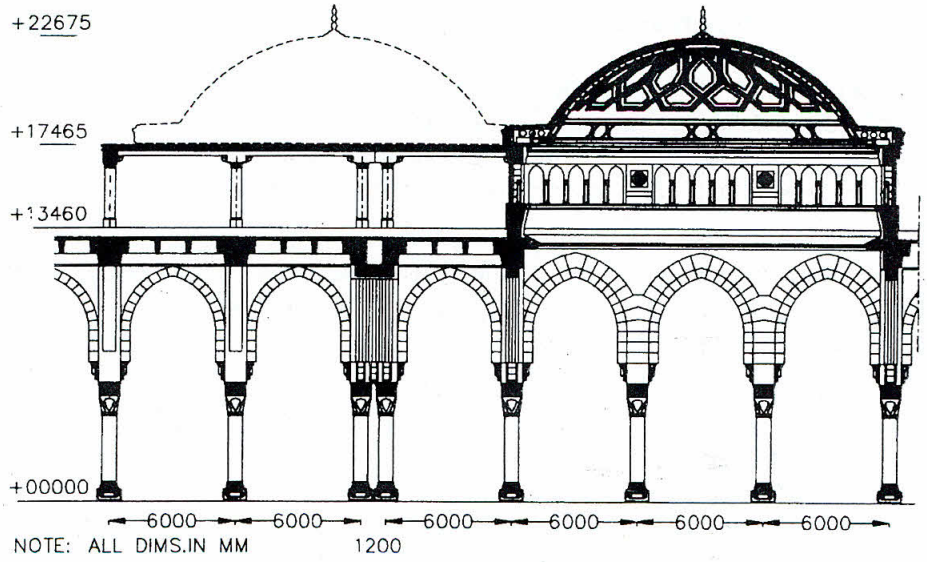


Fig. 1: Cross-section of a sliding dome showing the open and closed positions. [3]

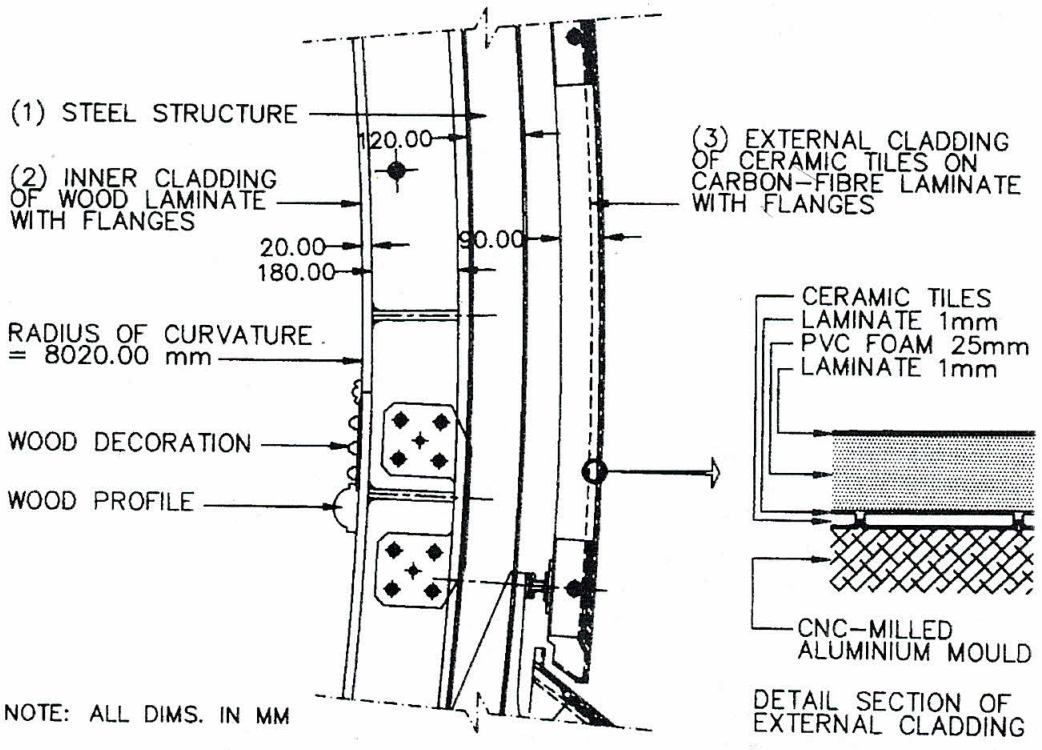


Fig. 2: Cross-Section of the Spherical Portion of the Sliding Dome. [3]

Design and Construction of the Sliding Domes

Technological adaptation of successful concepts from other industries to construction offers an opportunity for innovative progress. This is true in spite of the common belief that the construction industry has been viewed as a one-of-a kind oriented industry and as such unable to apply production methods developed for the manufacturing industry.[3]

This understanding was translated into the process for the design and construction of the Sliding Domes. In this process the dome was segmented into different components with different levels of repetitiveness, and the production methodology, including the use of robotics, was then determined for each.

The inner cladding was planned to be a composite wood laminate consisting of several layers of wood veneer bonded with epoxy resin. The entire shell was segmented into single parts that took advantage of repetitive operations and accommodated shipping requirements. Applied on these panels were decorative elements made of cedar wood on the inside and stiffeners and flanges on the outer side. The floral ornaments were designed to be traditionally carved floral pieces framed by a bold geometrical pattern of double-curved cedar wood profiles.

The outside panels were also subdivided into segments that would ship easily. But unlike the inner panels, designed to be a background for artisan work, these panels were industrially produced in every aspect. The design required flat and spherical panels covered with multicolor pattern of ceramic tiles. This design used a traditional Islamic theme: a band of turquoise tiles placed in a white background and separated by a golden contour.

The steel structure, waterproofing, insulation, driving system and assembly tools and materials were all manufactured according to established industrial processes. All components of the Sliding Domes were shipped to site for assembly where the knowledge and experience gained from building a prototype proved to be of great value.

The Planning and Control Model

The Prototype Approach in the Project

The Sliding Domes project was not a typical construction project. It was neither a pure building project nor a pure mechanical one, rather it was a blend of the two and lay in the overlap between the construction industry and the manufacturing industry. Although ultimately their domed form defines them clearly as pieces of architecture, their requirement to move and their subdivision into multiple sets of identical components does allow close comparison with a machine. Thus the decision to construct a prototype, although appearing very unusual in the context of a building project, appears totally normal and correct in the context of a manufacturing project.

As others have found, the use of prototypes and simulations in building design and construction enhances cost, schedule and quality control systems. [4,5,6,7,8] The benefits for construction applications of the prototype approach to the final quality of design, production and installation cannot be stressed enough. Such an approach will be seen as perfectly usual to those in manufacturing, but to architects and building engineers who are used only to the uniqueness of construction projects, the opportunity to have a second chance to refine their ideas after seeing them brought fully into reality was unique and stimulating.

For the production of the Sliding Domes, an approach using a series of individually built-to-fit domes could have been used. With such an approach, the time spent refining the prototype could therefore have been saved. In the prototype approach, the benefits that accrued during component production, segment factory-assembly and site erection were far greater. These benefits arose from two sources: interchangeability of parts and simplification through refinement of the details.

Interchangeability of components proved to be one of the primary keys to the project's success. Interchangeability was essential during the factory assembly of many of the decorative components onto the domes' inner cladding and during the site erection. A small proportion of the thousands of components would, inevitably, suffer some mishap and become damaged, including unfortunately one or two entire shell segments. If the discrete component approach had been used, wherein each component had been adjusted to fit in that location only, the time needed to organize production of a replacement would have been prohibitive. Interchangeability is possible only when identical parts can be produced, and this can only be achieved when proper industrial techniques are employed.

Post-production analysis showed that the use of the prototype sliding dome provided substantial reductions in production work hours and erection costs. It provided marked reductions in craft labor costs, helped reduce bulk material surplus and shortened the project schedule. Additionally, the approach proved to be an effective communication tool in bringing engineers, contractors and the owner together into a successful co-operative format, to the benefit of the project as a whole.

The use of this approach revealed that there needs to be a minimum number of repetitive elements in order to justify the expense of constructing a prototype. This minimum number depends upon several factors. These factors include: the type of material utilized; the opportunity to apply industrialized production processes; and the ability of the designer to sub-divide the element into repetitive and interchangeable parts. Other components of the Prophet's mosque project have benefited from the prototype approach both in design and construction. These components include: the mechanical umbrellas, the gates, doors, windows, and the lighting fixtures.

The Project Planning and Scheduling

Conventionally, the process of design, prototype development, approval and erection can be presented as a linear process. The Sliding Domes project involved an iterative process which complicated the planning model. Figure 3 illustrates this process.

The development of the prototype involved the design team working very closely with the lead architect for the Holy Mosque extension project. The process followed the ancient tradition of master architects whereby drawings are used as an initial guide to a design, while real decisions and creative assessments are made upon viewing samples and mock-ups. This approach allows judgments to be based on the true three-dimensional aspects of an object or the actual tone and texture of the materials.

The master architect approach can often result in an iterative repetition of the design, production and approval loop, as different aspects of the design were viewed and modified. The constraints of time or cost would normally guide a planner to establish a limit upon the number of repetitions of the design loop, usually two or three iterations at most. In a project where quality was the essential requirement, these design loops were entirely unfettered.

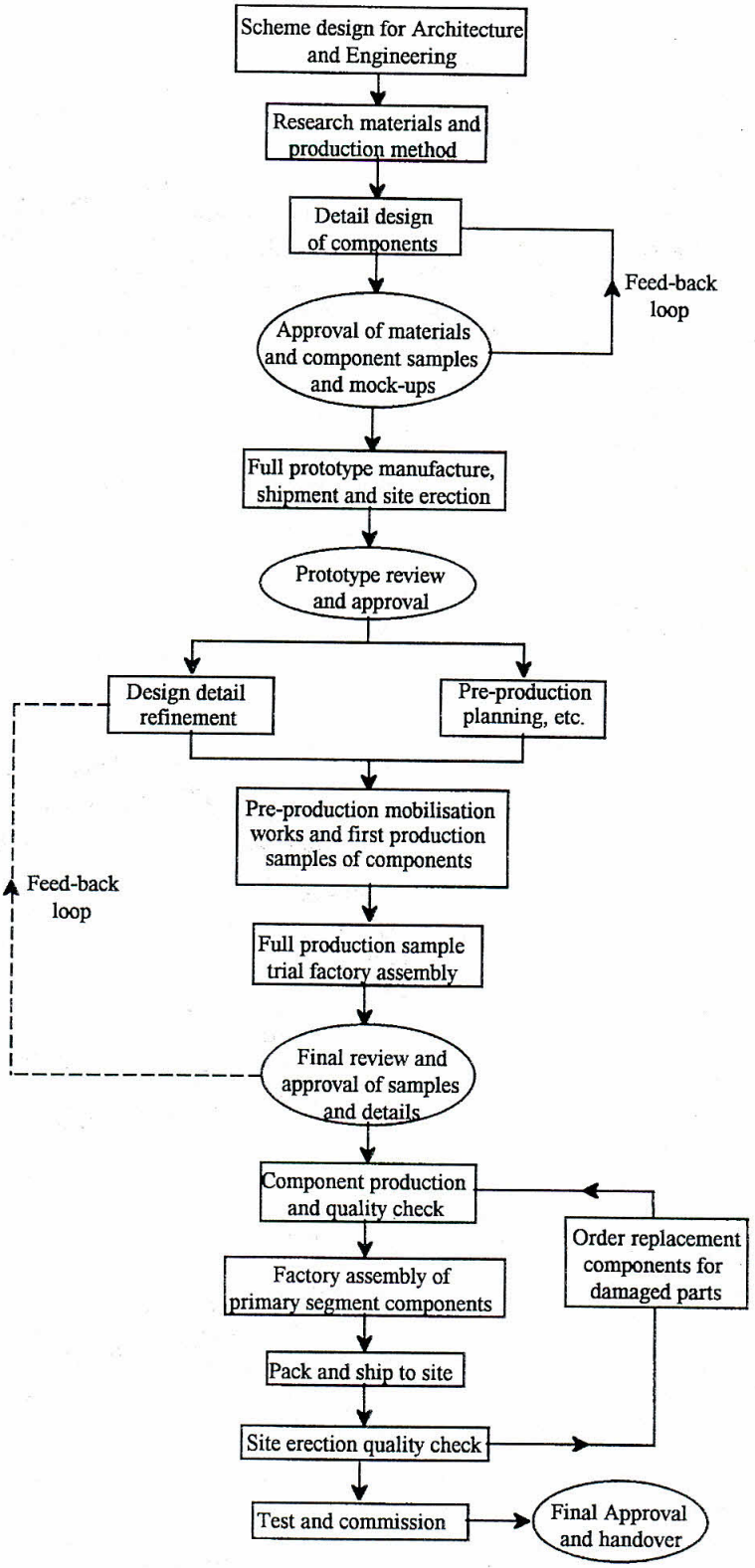


Fig 3: The project planning model.

It is rare indeed for architects and engineers to be free to work in such an environment, one that is usually only available to the artist. It is surely the presence of a "patron" rather than a "client" that defines this freedom. It was interesting to observe that this approach was not as profligate as might at first be suspected. Convergence to the optimum design occurred within perhaps double or triple the number of repetitions that would normally be allowed.

Once the prototype was approved, work started to construct the twenty seven domes. The size of the task in terms of number of suppliers, quantities of components and complexity of assembly sequence made the use of a critical path network essential to the planning, monitoring and control of the project. The master plan was created using an activity-on-the-node network and was modeled using standard microcomputer scheduling software.

Since the prototype had already established the majority of the materials and components required, it was obviously a proper decision to focus the network on tracking materials as the key aspect via which activities would be defined.

The many varied materials required for the domes could be broadly subdivided into two types: those produced largely through standard, industrialized processes, such as the steelwork frame or mechanical components; and those items produced by artists and craftsmen, such as cedar-wood carvings and the small decorative stones crafted from cobblestone-size semi-precious Amazonite.

As the project developed, it became clear that the different types of materials required different planning approaches. For example, the industrialized components needed planning at a relatively high, macro-scale level, with reliance placed upon the supplier to provide detailed planning and monitoring for the production targets. The ornamentation producers, however, required a far greater input both in planning and in monitoring their production. They had little experience of large-scale production and of the analysis, organization and control of repetitive processes. To reconcile this free approach with the disciplined industrial approach of the other contractors, computer-aided production of master templates and other devices was used to help the artisans produce their elements with the required level of predictable dimension and fit.

For all components therefore, the overall planning was carried out using the activity-on-node network and the basic timetable for production was established. The plan had to ensure that components would arrive at the required place at the required time for each dome individually. The main time constraints on the component timetables were the initial start-up activities at the front-end of production and the project completion deadline at the end. The planning for the craft-produced components made it necessary to work with the individual craftsmen to guide them to establish meaningful production schedules and daily priorities.

The project network contained approximately fifty activities for tracking the components of each dome, Figure 4. The total number of activities for tracking the 27 domes was thus well over 1500.

In building construction, the activity duration and the predecessor-successor logic define the construction schedule. However, the activities that control progress for the Sliding Domes construction project were linear in nature, but repetitively so. In pure linear projects such as the construction of a tunnel, the scheduling model is not accurately represented by the conventional critical path method and so the critical path method is thought not to be effective in monitoring progress and forecasting project completion for linear-type construction projects. [9]

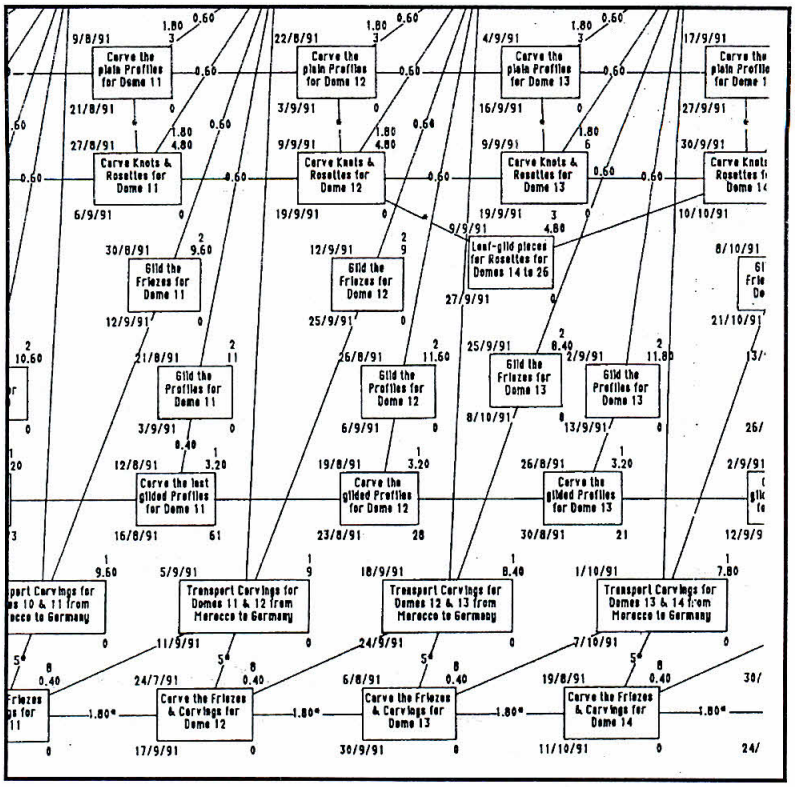


Fig. 4: The activity-on-node network with a matrix-like structure.

Being open to parallel working, a critical path network was used in this project. In addition to linking all the activities for one dome together, the project network also linked all the production activities for each type of component together. As a result, a network with a matrix-like structure was created. This network had of course one critical path. Because of the strict matrix inter-linking, it was possible to perform some simple sensitivity analysis on the network to ascertain which components were most susceptible to becoming critical should they suffer delay, and what magnitude of delay would cause this.

The structure of the network greatly supported the efforts of the planner in risk identification and assessment. It also allowed close monitoring of component production. Perhaps not surprisingly, it was the craft production of components from scarce raw materials that were most sensitive to delay. Examples of such materials include: the very large bulks of cedar wood available only seasonally in the Atlas mountains, and the rough Amazonite which was to be mined specifically for the project from the Kenyan bush.

It should be noted that the planning and scheduling of the Sliding Domes were carried out in the context of the total project of the Mosque extension. This consideration has guaranteed a proper level of integration with the different components of the project and made the Sliding Dome's control system realistic and successful.

The Project Communication System

Generally, a construction process model depicts the flow of project information through an information system. Such models are typically based on a human-centered approach and its applicability relies on the effective and willing participation of all project personnel.[10]

In the Sliding Domes project a human-centered system was utilized. The system facilitated the flow of project planning and control information provided by home-office and field managers through an effective mechanism. Project planning information was identified and generated for execution by the laborers using the specified project materials, tools, and equipment. Based on this process, information generated for evaluation provided a better understanding of the project and allowed better forecasting of future activities. Figure 5 illustrates the different components of the system.

Monitoring of the industrialized production was accomplished using standardized forms. Performance reports were usually faxed to the Sliding Domes sub-contractor's head office by the individual producers. Verification of the data was readily achieved through the official paperwork that accompanied each shipment to Saudi Arabia.

Monitoring of the craft-based production, however, became the aspect most critical to the final success of the project. As discussed earlier, the craft-based producers in this project, had little or no experience of the demands of mass-production. The sensitivity analysis performed upon the establishment of the Master Network had, as mentioned previously, identified the craft producers as those most at risk from becoming the critical, production-controlling factor.

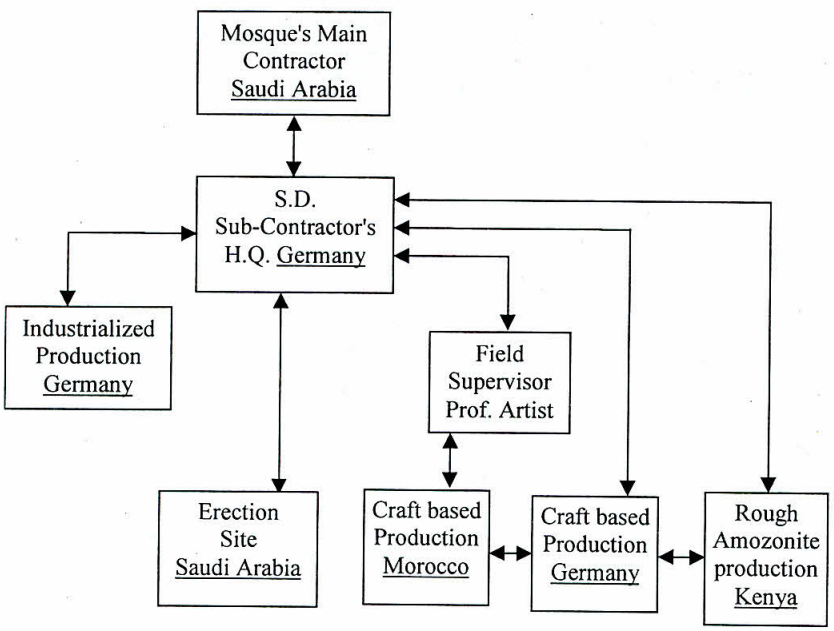


Fig. 5: The project human-centered information system

Initially, it was anticipated that the craft producers would manage their own production. It was thought that, once the basic timetable of deliveries was established with them, they would then simply organize themselves to achieve their commitments. However, within a

relatively short period, it became clear that some were struggling to establish any sort of production planning and management, and that a more involved, hands-on approach was required.

It was necessary, therefore, to work closely with the craftsmen to help them establish their work plans. The task required that the planner gain a detailed understanding of their work. It took some time and quite a few misunderstandings to establish the details, duration, and sequencing of the processes. The task was made no easier by language differences.

Even with basic work-plans, it proved very difficult to persuade the craftsmen to follow the given work schedules. They would quickly revert to their own, almost instinctive organizational methods. Simple charts and lists were used to communicate the weekly priorities, Figure 6. Weekly monitoring visits to the workshops were also necessary to keep production on track. The craftsmen were unfailingly keen to show what they had produced, but in their eagerness to achieve the production quantities to which they had committed themselves, quality was sometimes jeopardized.

Madinah Silding Domes - Moroccan Carvings - 10th November 1991

Code	Item	No.	Kuppel 1	Kuppel 2	Kuppel 3	Kuppel 4	Kuppel 5	Kuppel 6	Kuppel 7	Kuppel 8	Kuppel 9	Kuppel 10	Kuppel 11	Kuppel 12	Kuppel 13	Kuppel 14
			24-May-91	31-May-91	7-Jun-91	14-Jun-91	14-Jun-91	28-Jun-91	12-Jul-91	26-Jul-91	9-Aug-91	22-Aug-91	4-Sep-91	17-Sep-91	30-Sep-91	11-Oct-91
1a.	Chechia - 1/8th seg.	8														
1b.1	Sift A	8														
1b.2	Sift B	8														
1c.	M'tawa	16														
1d.	Mrbat	8														
1e.	Bokharia	4														8
2a.i	Double chain - upper	32														7
2a.ii	Double chain - lower	32														
2b.i	Geometric Frieze	32														
2b.ii	Geo. Frieze corners	4														

Shipped Approved Carved

Code	Item	No.	Kuppel 15	Kuppel 16	Kuppel 17	Kuppel 18	Kuppel 19	Kuppel 20	Kuppel 21	Kuppel 22	Kuppel 23	Kuppel 24	Kuppel 25	Kuppel 26	Kuppel 27	Extra
			24-Oct-91	8-Nov-91	19-Nov-91	2-Dec-91	13-Dec-91	26-Dec-91	8-Jan-92	21-Jan-92	3-Feb-92	14-Feb-92	27-Feb-92	11-Mar-92	24-Mar-92	
1a.	Chechia - 1/8th seg.	8						4								
1b.1	Sift A	8					6.5									
1b.2	Sift B	8					6.5						12			
1c.	M'tawa	16														
1d.	Mrbat	8					3									
1e.	Bokharia	4								2.5						
2a.i	Double chain - upper	32														
2a.ii	Double chain - lower	32														
2b.i	Geometric Frieze	32						18								
2b.ii	Geo. Frieze corners	4						2.5								

Fig. 6: Simple weekly reporting eased project progress communication.

Communication of accurate production data was naturally essential to monitor progress and to alert management of up-coming problems. To this end, the Sliding Domes sub-contractor employed field supervisors in Germany, Morocco and Saudi Arabia whose task was to report back each week essential field data such as the quantities of components in production, the quantities of components being shipped or being assembled on site. This enabled potential problems to be spotted early and allowed appropriate measures to be taken. Such measures included solving the problems in advance or adjusting the work-plans to sequence the problem item away from the critical path.

The Project Quality Standards and Quality Control

Quality Assurance (QA) and Quality Control (QC) are parts of construction quality management. QC is provided by the contractor to assure that quality construction is taking place and to assure that construction problems are avoided. QA is the means by which owners protect their interests [11].

Generally, in construction projects there are three basic variables that must be prioritized and then put into balance against each other: time, cost and quality. Working in one of the world's most holy places automatically defined the standard of acceptable quality required, quite simply, the very best that man could achieve. Time, in terms of completion date, was the next most important aspect, thus relegating cost to third place.

Specific procedures for quality control were used in the Sliding Domes project. Even though they could be viewed as typical QC procedures, their successful application required some adjustments to accommodate the unique aspects of the project.

QA/QC begins with a comprehensive design and detailed plans and specifications, followed by experienced project construction quality management. In the Sliding Domes project the design-build contractor produced all the necessary design details and standards for the proper production and installation of the Domes. The decision to use a prototype enhanced the effectiveness of the QA/QC system.

The highest quality standards were set for this project. This meant selecting the highest grades available for the chosen decorative materials, rigorous and repeated quality checks, high reject rates for the hand-made items, a 100-year design life for the mechanical and structural elements, and maximum levels of production accuracy at minimum tolerances. Although the latter brought about its own problems, it also of course brought great advantages in terms of component interchangeability and minimal site erection problems. For example if an item became damaged for some reason during transport or erection, it was a simple matter to swap a replacement out from the next shipment, confident that it would fit with its new neighbors.

Not withstanding the above comments, it was recognized that the quality of hand-made items using natural materials is not solely defined by geometric or other scientifically measurable variables but also by their visual aesthetic. Beauty is in part derived from the minor differences that come about instinctively from the hand of the artist as he works, and also in part from the natural variations inherent in the raw material itself such as its colour and graining. It was important therefore that the Quality Control procedures and rejection criteria struck the right balance between maintaining the highest standards of geometrical accuracy for ensuring component interchangeability whilst, at the same time, allowing the natural beauty of a craftsman's artistry to shine through and add an extra dimension to the overall aesthetic.

The arabesque panels, hand-carved from cedar wood which decorated the geometrical fields of the inner cladding, proved to be the most challenging in this regard. In order to achieve the quantities required, three separate workshops were established in Morocco from Rabat to Fez. Each workshop was controlled locally by a master craftsman. Raw timber was supplied from a central sorting and storage warehouse. Initially, the main contractor's representative in Morocco would visit each workshop once a week in turn and merely assess and report upon the quantities of carvings underway. However, as the first deliveries arrived in Germany, it became clear that the craftsmen were not paying sufficient attention to some of the simple but fundamental stages in their production.

For example, the application of shellac to the finished carving would not only bring out the full natural colour and beauty of the wood but would also accentuate any color differences between the planks used to make up the base board, giving a strong stripe through the finished carving. Normally, the carvers would not be concerned about this aspect, seeing it merely as a natural, random result. This project required a higher standard that blended the best of machine production with the best of human production. The problem was of course readily solved: the planks for each carving should simply all come from the same original bulk. The main contractor had to employ a professional German artist to take on overall supervision for all the workshops and personally assess each arabesque before, during and after carving. The solution resulted in sending most pieces back several times for re-working before they could be finally signed and allowed to be packed and shipped to Germany.

On arrival in Germany, the carvings would be assessed again, this time to select sets of carvings to make up a single dome. These decisions are by their very nature subjective and potentially arbitrary, therefore the key to implementing and maintaining consistent standards was to put the responsibility solely into the hands of a single individual. As is so often the case, the assignment of the individuals for performing the final quality checks on each of the different elements usually came about by the chance presence of someone already working on some other task involving that material who had the necessary eye and sensitivity to make the right choices.

The Construction Management Team Organization

The organizational structure and processes of the construction management group affect the cost, quality, and duration of any project. The group's functions directly add to the overhead of the parent organization and therefore only value-adding functions are needed.[12] The value-adding functions are usually related to working closely with customer needs while considering the parent organization's requirements in project planning and control.

In the Sliding Domes project, the sub-contractor made the decision to directly employ the least staff. Experts were employed for the design, the production and site erection stages. All the production tasks, the packing, the transportation and the erection labour was provided by the project sub-contractors.

The Sling Domes sub-contractor therefore, had a very flat internal organizational structure for the project management, with almost all individuals reporting directly to the General Manager. This would normally necessitate intense involvement from the General Manager who would be key to coordinating the work of the team rather as a conductor directs the members of an orchestra. However the Sliding Domes sub-contractor, unusually took the flat organizational structure one stage further by giving each individual the autonomy to direct the work in which he is engaged, and the responsibility to co-ordinate his work with that of his colleagues. The comparison can be drawn then not with an orchestra controlled by a conductor, but with a folk group ensemble composed of highly skilled individuals. In this setting, each team member will be involved in their own task, taking and then giving the lead informally around the group as the composition develops, and together creating something of beauty, substance and complexity.

Such an unusual structure and form of team work places unusual demands upon the individuals who work within it. Those who thrived on the autonomy-with-interdependence took up the challenges and derived great personal satisfaction from their successes. Others, who could not adapt to the seeming lack of 'formal' control and direction from above quickly moved elsewhere.

One of the strongest factors behind the success of this project was the absence of interaction boundaries between all participants, including the patron client, general contractor, master architect, consultants and the Construction Management team. In fact, the general contractor provided the CM team with permanent office facilities that enabled productive co-operation and instantaneous interaction to readily occur. In this way, the traditional contractual and confrontational attitude was transformed into a single team, single mission relationship.

Driver-Based Management

Most projects are planned using known facts, historical data, and in the absence of the former, best estimates. Estimates take the form dictated by one's history of experience and are generally based on previous successes and the measures used to evaluate them.

One of the outcomes of this process, for example, is that the budget estimate is often 're-cast' as a control estimate at a later stage. Coding of costs also varies from one company to another, making effective and consistent exchange of information for progress reporting, billing and payment difficult. In addition, many of the project control systems used now are complex in order to meet the needs of today's demanding project and data acquisition requirements.

Projects now face many new challenges; two that seem to dominate are the growing uncertainty of project outcomes, and the strategic need to reduce overheads of all sorts.[2] Such challenges dictate the need to maintain consideration of risk and strategic drivers for the project concurrently during its entire life-cycle [1]. The risk drivers identify the project attributes necessary to reduce the level of risk or to reduce the uncertainties in the risk estimates. The strategic drivers provide additional project attributes to monitor and facilitate control of the project.

In order to encompass the above concepts in planning and control procedures, a management approach was used that the authors have termed 'driver-based management'. The approach uses the project risk and strategic drivers as the basis from which to identify a single common measure for planning and control. The single measure is the project deliverables, the tangible elements that are produced as the project develops.

In the Sliding Domes project for example, the main risk driver, as previously described, stemmed from the strict quality standards. The main strategic driver was the obligation to succeed. Comprehensive effort was used to clearly identify the project deliverables in light of the identified project risk and strategic drivers. The careful analysis, that involved the project team, identified the project deliverables as:

- the timely delivery of dome components to the erection site at the specified quality;
- the timely erection of the domes components at the required specifications.

Associated with each of the project deliverables, the driver-based management system requires an estimate of the cost and number of work hours. Those are measured as 'budget', 'actual cost' and 'projected final cost'.

In order to avoid optimistic forecasting, estimates should be compiled using conventional tools for risk management such as the Monte Carlo technique. The result is a range of possible outcomes that forms the basis of the budget and the schedule. After the selection of the target cost and completion date using acceptable probability of success or failure for the project, an appropriate cost and time is then allocated back to each deliverable.

During implementation, simple measures that rely on the bare minimum of cost codes, current at any one time in a project, can be used for data collection. Reporting of project progress can thus rely on conservative approaches such as measurement of earned values. Such an approach protects against the optimism biases typical in self-reporting. In order to ensure effectiveness, self-reporting should show immediate feedback of value to the reporter.

In the Sliding Domes project, even though project deliverables estimates were performed using deterministic values, proper contingency duration and cost were used to deal with the identified project risks. The human-centered information system based on self-reporting by the project management team members proved to be effective in the project progress reporting. Frequent progress meetings were conducted at the Sliding Domes sub-contractor's office. The flat organizational structure of the project management team guaranteed fast and effective communication.

Conclusion

The Sliding Domes project has proved that the adverse effect of physical distances between the construction site and the locations of production operations is rapidly losing importance. This was demonstrated by. how resources as well as design and construction processes in four continents were integrated and brought together to build a fitting and functioning part of this magnificent edifice. The project represents a real-life example of advanced planning, scheduling and control procedures. Such procedures have made it possible for the complex design and construction of the Sliding Domes to be completed in a successful, economic and timely manner.

The planning and control procedures that were used for the construction of the Sliding Domes in the Prophet's Holy Mosque in Madinah utilized a conceptual frame work that the authors have termed 'driver-based management'. Similar to approaches others have recommended, the driver-based management technique utilizes the project strategic and risk drivers to identify simple measures for project success. The suggested project measures, namely, the project deliverables are then used for planning, control and data collection. The approach, by using a single success measure, avoided the need to convert one type of estimate to another as the project moves from one phase to the next. The driver-based management approach proved effective in this application. The approach can be more effective when used in combination with risk management tools.

This methodology was enhanced in the Sliding Domes project by several unique factors. These included the effective utilization of the prototype approach, the successful reconciliation of the artistic free spirit with the disciplined industrial processes, and the elimination of interaction boundaries between all participants in the project. In addition, the experience revealed the need for additional research into the technical and economic feasibility of some of the practices used, particularly the prototype approach and the interchangeability of elements, and for research into their impact on the planning and control of construction projects.

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أنظمة التخطيط والتحكم في مشروع تشييد القباب المتحركة بالمسجد النبوي بالمدينة المنورة في المملكة العربية السعودية

د. خالد عبد القادر طاهر

قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود

الرياض، المملكة العربية السعودية

د. فؤاد الريحاني

مجموعة بن لادن السعودية

جدة، المملكة العربية السعودية

د. محمود راش

زوندر كونستركشن وليختباو (SL)

لينفيلدن، أوبر آيخن، ألمانيا

م. بنت كيسر

شركة بورو هابولد

الرياض، المملكة العربية السعودية

ملخص البحث: تعتبر توسعة خادم الحرمين الشريفين الملك فهد بن عبد العزيز للمسجد النبوي بالمدينة المنورة الأكبر حجما والأكثر تطورا في تاريخ عمارة المسجد النبوي الشريف. وتعتبر القباب المتحركة من أهم السمات الإبداعية في هذا المشروع العملاق. لقد تم تنفيذ سبعة وعشرين قبة متحركة لتغطية الساحات الداخلية المفتوحة بالمسجد والتي بلغ عددها سبع وعشرون ساحة. وبالإضافة إلى كبر حجم تلك القباب، حيث كانت أبعاد كل منها ١٨×١٨ مترا، فلقد كان تصميمها معقدا وخضع لمعايير جودة عالية جدا، الأمر الذي حتم استخدام تقنيات حاسوبية متطورة سواء في مرحلة تصميم أو تنفيذ أغلب أجزاء هذه القباب. يشكل مشروع القباب المتحركة مثالا حيا لتطبيق تقنيات متقدمة في تخطيط وجدولة ومتابعة المشاريع ولقد ساهمت هذه التقنيات المتقدمة في تصميم وتنفيذ المشروع بنجاح وضمن التكلفة والمدة الزمنية المطلوبة.

تصف هذه الورقة مشروع القباب المتحركة والعوامل التي أثرت في تصميمه وتنفيذه. كما وتناقش الورقة التقنيات التي استخدمت في التخطيط والجدولة والتحكم في هذا المشروع. كما وتستعرض الورقة أسلوبا إداريا أطلق عليه اسم "الإدارة المبنية على الموجهات" أستخدم بنجاح في إدارة هذا المشروع. وأخيرا تناقش الورقة استخدام نموذج مصغر للقباب أثناء مرحلة التصميم، ساعد كثيرا في مرحلة التنفيذ حيث سهل عمليات التخطيط والمتابعة. هذا ويعتبر نجاح هذا المشروع اكبر شاهد على فعالية هذه التقنيات في المشاريع المتقدمة.