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Architecture in Motion

Drive and Control Solutions in Architecture

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1. Abstract / Introduction

Architectur(e) in Motion – by looking at that phrase there are two important words in it "Tech"nology and “E”motion. That is exactly, what makes this design and engineering so special for these kind of applications. From big cylinder applications with kinematics to gear motors and precise controlled movements of huge and heavy elements. There are no standard solutions, because every building or application is unique and designed for its own purpose.

Regarding big public events, since a thousand of years architecture has been fascinating millions of people. During the ancient time of the Romans, people moved into the Colosseum of Rome to watch the events there and to be impressed by the architecture and the atmosphere inside the arena. 2000 years later the arenas are based on the same shape, but the functionality has changed completely and cannot be compared to the ancient arenas anymore. Nevertheless, this ancient arena had already many modern elements, like retractable membrane roofs and complex lifting units to entertain the audience.

The arena design itself made a very dynamic improvement progress during the last years and were adapted to today´s needs of modern, flexible multi-function arenas so that retractable membrane roofs and grandstands, sliding pitches, modular pitches are used to increase the possibilities of their usage.

Not only stadiums will be designed for more flexibility, but also shopping malls, high towers and big buildings will be equipped with some dynamic movable elements, retractable open air areas or sightseeing attractions to have them be more attractive and to extend the stay of the visitors.

All these dynamic elements and subsystems in Architecture have enormous size and weight, which requires a special design and the need to consider the final application. In most cases, the required drive technology needs to be small, noiseless, reliable and “invisible” (and inexpensive) in some way.

Due to the fact that a lot of stakeholders are involved in these kinds of projects such as, the design architect, the architect of record, consultants, General Contractor and many suppliers with different scopes, it is a very long difficult journey from the first idea to the final solution. As a drive and control specialist you have to be involved from the very beginning to influence the design to find the best solution for the application.

The paper gives an insight based on sample projects like Amsterdam Arena, Caja Magica, Schalke Arena, Plaza Illumbre, ... , how Bosch Rexroth did the design and engineering of the drive and control system by starting from a blank sheet to the final commissioning.

2. Architectural Aspects

Convertible roofs and structures in Architectures have been built for centuries and there are various forms of historical retractable roofs. Beginning with the Tipi tent from the Indians and other tent variations from Asian and African nomads to the Colosseum in Rome all these architectural structures had already some kind of a retractable roof.

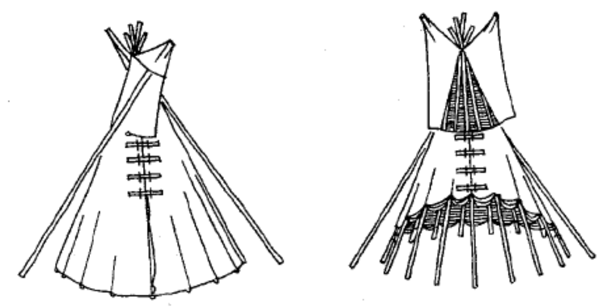


Figure 1: Indian Tipi [4]

The reconstruction of the Roman Roof showed that the basic type of the roof consists of wooden poles and vertical rods, which is moved by the connected ropes. The angle of the roof itself and the maximum roof size can be adjusted by pulling the ropes in accordance with the sun.

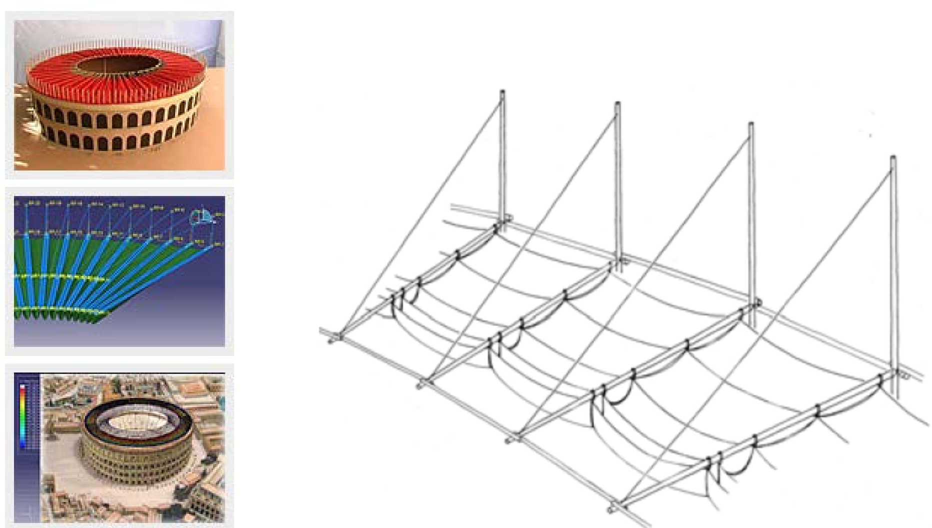


Figure 2: Reconstruction of Membrane Roof of Colosseum Rome [2], [5]

In 1964 the German Architect Frei Otto founded the “Institute for Lightweight Construction” (ILEK) that worked systematically on retractable roof design. The following design matrix was developed by Frei Otto and his team for a classification of convertible elements in architecture. The design matrix shows the distinction between rigid and “soft” membrane constructions. Combined with the direction of movement the matrix defines all possible forms of convertible roofs. Also the membrane design structure will be tensioned by hydraulic actuators so that in the end they can also be regarded as a “stiff” structure.

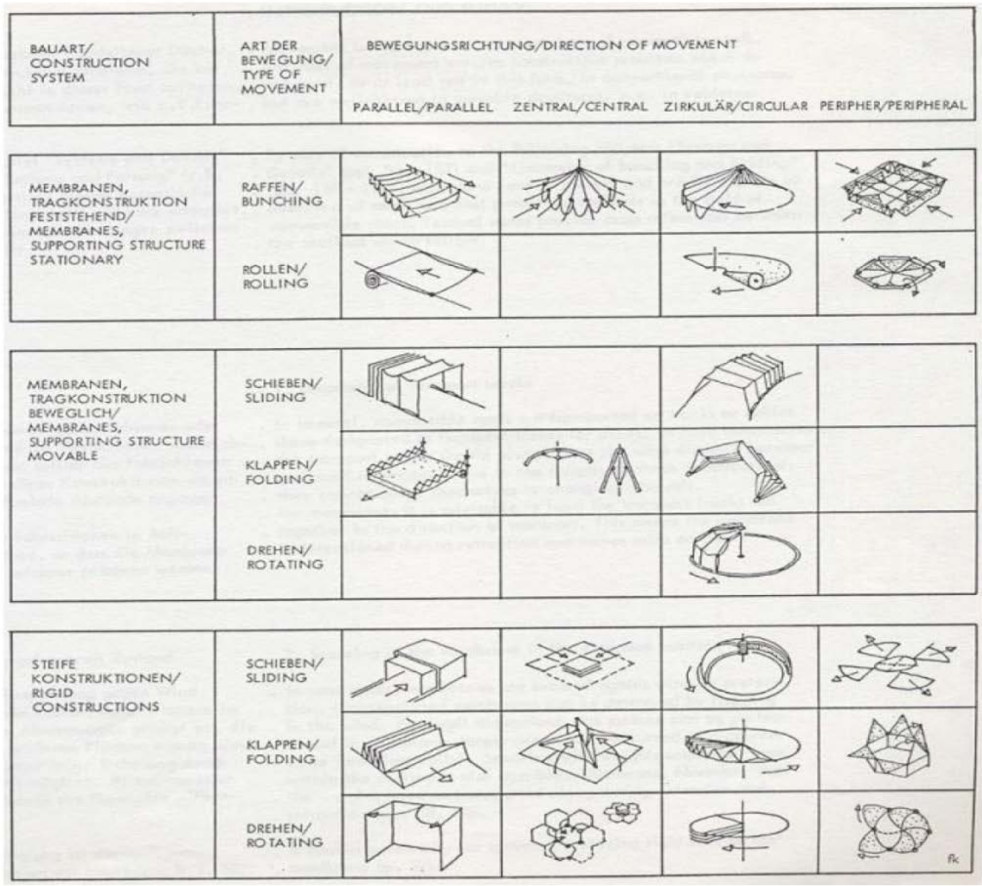


Figure 3: Movement Matrix by Frei Otto 1964, IL5 Stuttgart [3]

It is surprising to see how many modern arenas are already built based on this design matrix considering these basic moving principles.

Figure 4: Stiff construction / circular- (Civic Arena, Pittsburgh, US) and Membrane roof / central- movement (Commerzbank Arena, Frankfurt, Germany)


Figure 5: Stiff construction sliding / parallel-, central- movement (Amsterdam Arena, NL, Schalke Arena, Germany) [17]


Figure 6: Stiff construction folding central / membrane construction central (Caja Magica, Spain, Banda Aceh, Indonesia) [17]

Regarding the complexity of these design approaches, an early involvement of all relevant parties is essential for the success of these projects, beginning with the design architect, the architect of record, consultants and general contractors.
For movable structures with huge spans the own weight of the structure itself is the most important criterion, which dominates the geometry of the roof design, the material and the drive and control concept (power requirements, drive principle).

3. Drive and Control Design

Depending from the design, the Drive and Control concept could be very different. For most of ridged constructions, technology of movable cranes is used. A rail system with bogies is the most common design approach. Also all rules and regulation from crane technology (e.g. ISO8306 for crane tracks) can be used for tolerances and deflections of rails and the roof design.

A typical opening time for a sport stadia roof is in the range of 10-20min for both roof halves together, depending from the rules and regulation of the sport event. For a football match the decision to close the roof is done before the match, so 20min will be sufficient, for Tennis matches it must be quicker, because the match must be continued in a certain time range, without a longer interruption for the players.
Depending from the size of the roof one roof half can have a weight of 200 metric tons for a smaller size roof (20.000 seater stadium) and up to 600 metric tons for a roof half of 70m x 83m. The inclination, or slope of the roof track also has to be considered for the drive and control system like special weather conditions e.g. snow loads or high winds. By considering the relatively

low opening /closing speed of the roof in most cases an electric motor with a gearbox is used to operate the system. Each motor is controlled by a variable frequency drive utilizing power generation (VFD). In some cases, a special gearbox motor with integrated frequency converter (VFD) can be used to design the systems as smart as possible. The electric power for one motor will be in the range of 5,5kW and the planetary gear box ratio is in the range of 100-600 to give some ballpark figures for a typical 600 metric ton roof with 18 drives per roof half (9 motors/side).

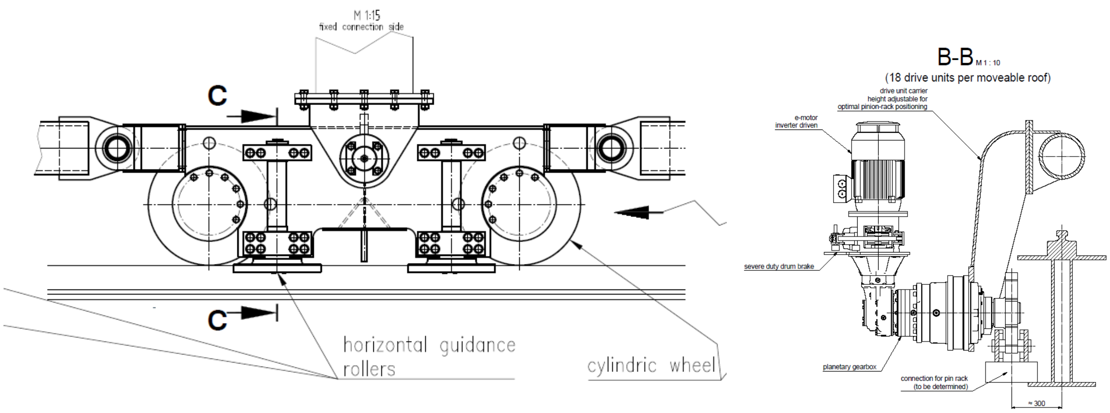


Figure 7: Bogie with lantern gear drive unit (design for France Rugby Stadium) [17]

For converting the rotational motion into the linear movement, the standard approach rack and pinion is most common, but also a lantern gear can be used, which is less sensitive for mechanical tolerances, caused by the mechanical load and temperature. For non-sloping roofs a simple wheel rail approach from railways can be applied, which provides the simplest and a robust solution for service and maintenance.

Figure 8: Rack and pinion drive unit (Amsterdam Arena left, Plaza de Illumbre, Spain, right) [17]

The lateral guiding of the roof structure must be secured by guiding units at minimum on one side and must consider (avoid) the static overdetermination of the structure.

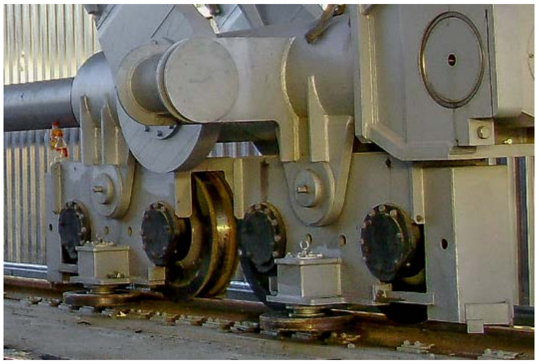


Figure 9: Bogie systems with lateral guiding units (Caja Magica, Spain), [17]

In any case a locating/floating bearing arrangement must be foreseen for the structure to compensate the tolerances from structure itself and the rails systems and also the influence of the thermal extension cased by sun radiation and day/night shift.

From the drive an control aspect the main important issue is the synchronisation between all drive units, acting on both sides of one roof half. If the deviation between the drive units is too big, mechanial tolerances will be exceeded and result in mechanical stress for the structure, which must be avoided in any case to protect the drive system and also the mechanical roof structure.

In principle a roof drive system could be equipped with hydraulic standard motors with gearbox, or hydraulic direct drive motors (low speed, high torque) without a gearbox. Some detailled technical and commercial calculation showed that the electric solution has some advantages regarding the price and less installation effort, if the purpose of the hydraulic system is only used for moving the roof.
This situation is different, when some hydraulic units are foreseen for some other additional functions, in this case it makes sense to make a detailed cost and effort analysis to compare both solutions against each other.

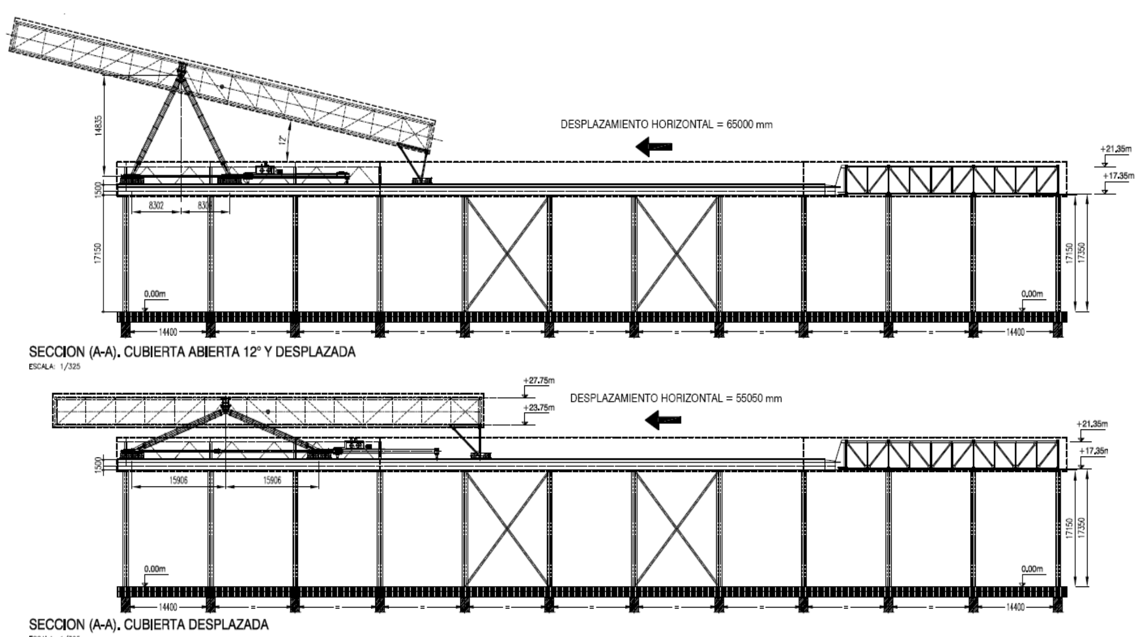
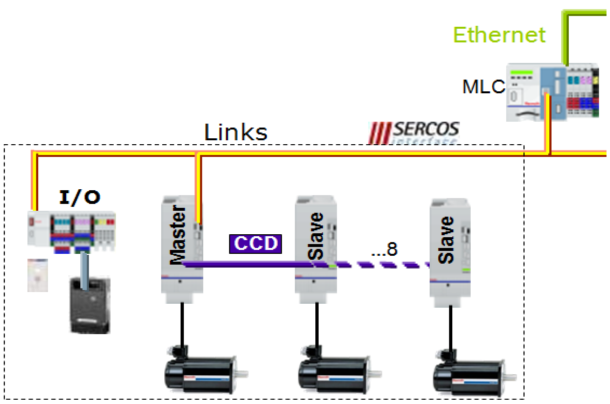


Figure 10: Hydraulic moving and tilting design principle Caja Magica, Spain [17]

The Caja Magica Tennis stadium in Madrid (Spain) is a good example for this particular case. For lifting the huge roof (1800 metric ton e.q. 5x Boeing 747) a cylinder system is used for lifting/tilting and the drive unit of the roof is also done by a hydraulic motor incl. gearbox.

Figure 11: Hydraulic tilting unit with cylinder (left), hydraulic drive system (right) Caja Magica, Spain [17]

Form the control accuracy there is no difference between an electric and hydraulic driven solution both approaches work with the same high level of precision in a closed loop system.



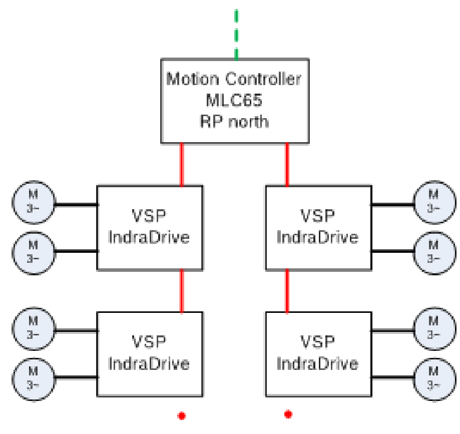


Figure 12: Control structure for synchronization of roof drive system [17]

Figure 12 shows the local control structure for synchronization of each motor and also the "right and left" side of one roof half. The Master/Slave application between the drive units is used to synchronize the drive units acting on one roof side by an internal CCD Bus (left).
The "global" synchronisation of left and right roof side drive is done by the motion control system, in this case by a MLC 65 and the realtime SERCOS Interface Bus.

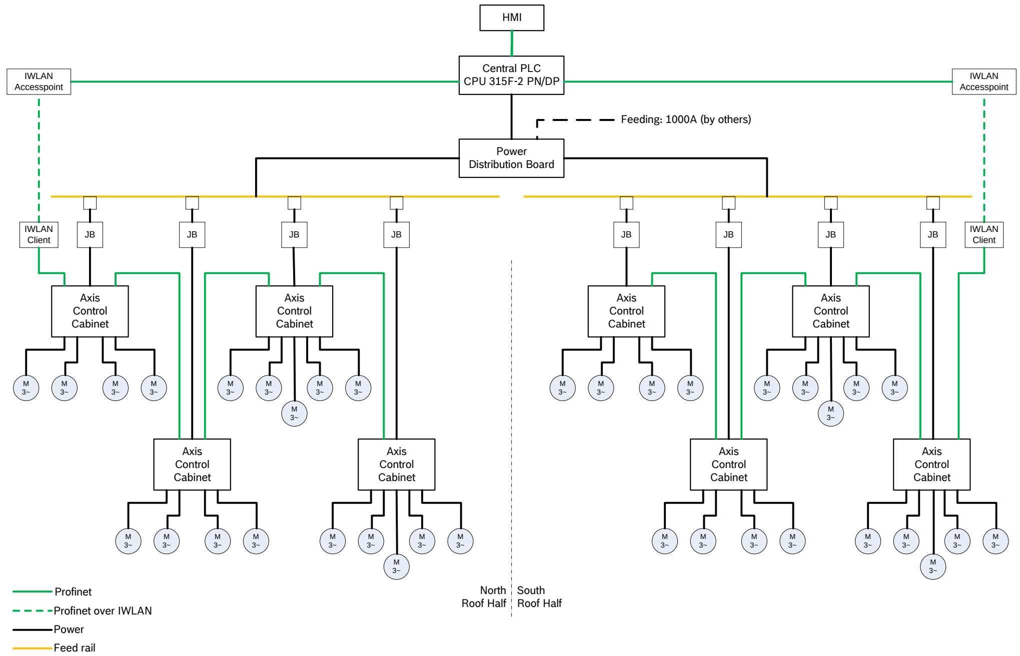


Figure 13: Full control structure for a retractable roof with 18-drive units/roof half [17]

A sample schematic for a full control system of a retractable roof incl. all electrical drive units is shown in Figure 13. The HMI-system is connected via Ethernet to the central PLC, which communicates via an Industrial Wireless LAN (IWLAN) access point with the two roof parts (RP). All axis control cabinets are also connected by an IWLAN client to communicate with the Central PLC unit.

General remarks:
The application specific aspects mentioned in this paper are not only valid for a stadium roofs, but also can be used for any kind of big roof drives, independend if it is a stadium roof or any other roof drive application of heavy weight and huge size.
Actually the latest trend for shopping Malls is to equipe them also with a retractable roof to open it in the morning or in the evening to have a more open atmosphere like a traditional plaza.

The ideas in general vary from retractable shading elements like XXL-Umbrellas or foldable membrane elements, up to slidable glass top roofs, which allow an airconditioning of the shopping area or plaza.

4. Simulation and Engineering

Today´s modern engineering methods make it possible to investigate different drive solutions from the very beginning. The simulation of the application must have a special focus. Simulating every aspect of a system makes no sense and increases the required computing time up to a level, which is not practical for daily business.

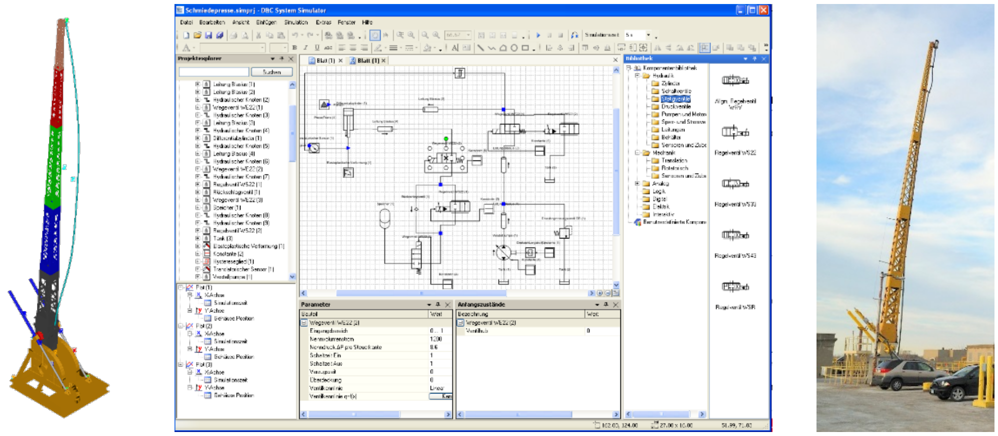


Figure 14: System (co) simulation of drive unit and mechanics of a ship arrestor by SysSim (Tool - Bosch Rexroth AG) and ADAMS (MSC-Software), Welland Canal (Canada)

Regarding the drive system for the roof drive or bridge, or any other civil engineering application the following topics could be part of the numerical simulation:

- Comparison of different drive solutions incl. mechanics
- Engineering of the drive unit (size and number of actuators, size of motors, ...)
- Energy consumption (per cycle, per day, week, year, TCO, ...)
- Dynamic behavior of the whole system (drive system + mechanics) during regular operation
- Virtual test of emergency situations (shut down time, wind gusts, malfunction of subsystem, ...)
- Virtual test of winter / summer operation (ice load, wind, low/high temperature)
- ...

The system simulator software (SysSim) provides interfaces to all common engineering tools. It enables virtual engineering together with the customer and other suppliers during the early engineering phase. This powerful method can be used for engineering and optimizing any civil engineering application to secure the function of the system and to save commissioning time. From the customer point of view “his solution” is already proven, virtually commissioned and the chance of “big surprises”, is reduced to a minimum.

5. Engineering and Project Workflow - early involvement vs. late entry

The PMI standard process (www.pmi.org) defines the following Project Management Process Groups: Initiating, Planning, Executing, Monitoring/Controlling and Closing.
For larger infrastructure projects like arenas, stadiums or big bridges, the period can cover a range of 5-7 years from the “first sketch” until the final opening.

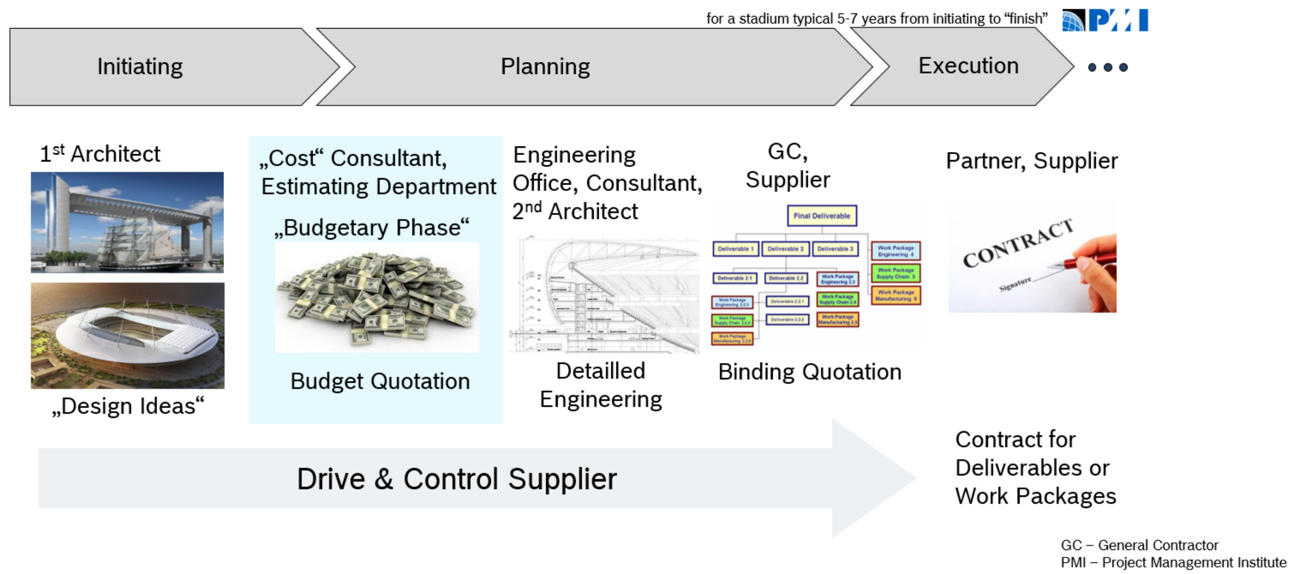


Figure 15: Process workflow for large infrastructure projects based on PMI Institute www.pmi.org, Pennsylvania

At the very beginning a 1st Architect, or Engineering Office who/which is responsible for the design of the project (stadium, bridge ...) are focusing in most cases on the outer shape and do a basic mechanical design with some ideas about the drive system.
Based on that documentation the most important "Budgeting Phase" for large projects starts. The cost of all deliverables are summed up, to calculate the overall budget for the whole project. This budget number is in most cases used later by owner for funding, or the authorities, who are sponsoring the project.

The risk for a supplier is that he could:

- Quotes too high ("afraid of risk")
- Quotes too low ("not enough knowledge, or too less information")
- Quotes too slow ("too much work required to quote an accurate price")

Quoting to high is understood. By bidding to low a supplier, will not be recognized as a serious partner for that project. Quoting too slow, may be due to the fact that all parameters like forces, torque, speed and other system parameters cannot be given in detail at this state of the project (only rough data are available). This requires the supplier to make assumptions to continue the engineering and to remain in the bidding process. The alternative is to wait until the detailed specification is finished in a later phase of the project. In this case all chances are gone, to influence the design ("take it, or leave it"). This is an appropriate strategy for selling commodity products, or products off the shelf, if your pricing reaches the right (low) level.

The big chance of an early involvement in the project is that some design parameters are still open. The specification of a lifting bridge drive system can be opened for a hydraulic drive system as an alternative instead, or additional to the standard electric drive with gearbox. A detailed technical and cost comparison can be done in this phase for both alternatives (electric vs. hydraulic drive system).
If the selection of one drive solution is done in this early phase (by missing alternatives from suppliers), the chance is gone, because when the final design specification is approved, there will be no chance for any alternative solutions.

When the total budget is approved by the authorities or owner, the detailed engineering phase follows and is done by a second architect or/and specific consults. The output is the detailed specification, which will be addressed to the selected general contractor, or to all general contractors on a “short list”.
Each of the GCs will prepare a binding quotation for the overall project and split the work packages and deliverables to all supplier, after getting also binding quotes from them based on the final specification.
The key success factor for a large project like a retractable roof, or bridge application is the cooperation between architects, civil engineering and mechanical engineering firms. Especially the interfaces and responsibilities have to be defined precisely during the planning phase e.g. locking the roof in different positions, accessibility for service and maintenance, fixed/floating bearing of structure, thermal extension. All these aspects, which are not considered here, will be very difficult to fix on site later and may result in delay or additional costs of the project.

Most cost increases in large projects are the result of non-precise budgeting. Reasons could be: a try to get the order, to push out competitors, or to get the project financially approved by the authorities or owner. Later design changes in the detailed engineering phase will show the “truth”, if the previous design and budgeting work was done seriously. The budgeting phase is one of the important phases for large projects and much more than “only for budgeting”.

The whole workflow of the engineering phase shows how long it will take from the first sketch to the binding quotation, but this opens in many cases the chance to influence the design and to bring in special branch knowhow and prevents a “late entry by price” for the already final engineered solution.

6. Conclusion

Regarding the design of modern arenas and stadiums with movable elements like retractable roofs, pitch (playing field), grandstands; this allows the owner to extend the usability of the stadium itself to any other event like concerts, sports- and nowadays “eSports-” events, public activities … and under the bottom line to increase the overall turnover. In addition, shopping malls can be designed more attractive by using dynamic architecture (e.g. slidable roofs, moving sculptures …) to extend the stay of the visitors there.
All these projects will have a long term design, planning and construction phase, which can last up to 7 years from the first sketch to the final solution.
It is essential for these kind of projects that the supplier of the drive and control system is involved in a very early phase to find the best solution, which is an integral part of the architectural design. The drive solution should not “destroy” the architectural design and should be smartly integrated. The decision if an electric or a hydraulic drive system is the best solution, must be decided from case to case focusing on the overall drive and control package, some examples are shown in this paper.

Regarding the modern engineering tools a lot of the engineering work can be done virtually to prove the design. In the end all partners like architects, designers, suppliers, general contractors, operators have to execute the project effectively in the real world. A key success factor is the collaboration of all involved parties especially in the early design and budgeting phase.

In general the drive and control supplier for large projects should act more as a partner than as a pure supplier. Delivering innovative customized Drive and Control Solutions, excellent components (independent from the technology electric or hydraulic drive technology) and a professional project and site management is essential. This guarantees the success in this business from the first sketch to the final unique solution.

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