Schedule and Cost Estimate for an Innovative Boston Harbor Concert Hall

by

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B.S., Civil and Environmental Engineering
Ecole Speciale des Travaux Publics, 2003

Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Engineering in Civil and Environmental Engineering

at the

Massachusetts Institute of Technology
June 2004

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ABSTRACT

This thesis formulates a cost estimate and schedule for constructing the Boston Concert Hall, an innovative hypothetical building composed of two concert halls and a restaurant. Concert Halls are complex and expensive structures due to steep design requirements reflecting their status as signature buildings and because they require extensive furnishing. Restaurants are not as complex but require the same kind of attention in their interior furnishing as well as in the choice of their kitchen equipment. Because the structure houses two complicated entities, feasibility analysis required a careful cost and schedule estimation.

On the basis of several assumptions, a rough estimate of the cost and schedule of the entire structure has been developed along with a more detailed estimate of the two auditoriums and the restaurant. The study suggests that the interior finishing of such unique buildings represent a large fraction of their overall costs and construction time.

Thesis Supervisor: Nathaniel Osgood

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ACKNOWLEDGMENTS

I would like to thank God for His love and comfort to me during the year. Since I became His child by faith in Jesus Christ His son, He has always guided me in His ways and I couldn't have come here without Him.

I would like to thank all my family who has always helped me. I couldn't have come here without their support and I thank them for having guided me in the ways of the Lord Jesus Christ for so many years.

I would also like to thank Doctor Connor, who has been of great advice this year when choosing my classes and always of good support.

I would also like to thank Doctor Osgood who helped me so much to put this thesis together. He guided me very diligently when trying to find information, gave me some really good piece of advice and was of great support when it came to editing and formatting.

Finally, I would like to thank my sweet roommates, my classmates at MIT, my classmates in France and my three dear churches in St-Denis, Houston and Brockton. They have encouraged me by so many emails and comforting words all along the year.

It has been a great year!

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This thesis formulates a cost estimate and schedule for constructing the Boston Concert Hall, an innovative hypothetical building composed of two concert halls and a restaurant. Concert Halls are complex and expensive structures due to steep design requirements reflecting their status as signature buildings and because they require extensive furnishing. Restaurants are not as complex but require the same kind of attention in their interior furnishing as well as in the choice of their kitchen equipment. Because the structure houses two complicated entities, feasibility analysis required a careful cost and schedule estimation.

This section reviews the central elements of the structural design of the facility whose cost and schedule is estimated by this thesis. The section first examines the architectural concept underlying the structure, then turns to a discussion of the structure and finally examines the motivations behind the project.

1.1 THE ARCHITECTURAL CONCEPT

1.1.1 A ship

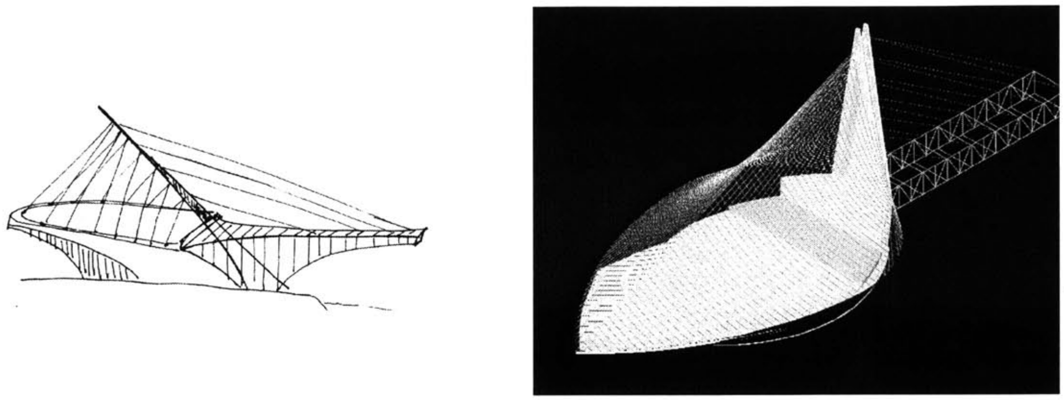


Figure 1: Ship Rendering

The design of the Boston Concert Hall builds upon a ship motif. The architectural concept of the ship was a response of the already prominent maritime theme in Boston. The concert hall offers two auditoriums on the ground, one on top of the other (left in Figure 1). The venue on the first level houses 1500 people, the one on the second level 5000 people. The right side of the structure (See Figure 1), suspended above the water, is a glass restaurant.

The shape of the different areas and the way they are connected depicts the skeleton of a ship. The 300 feet tall concrete tower symbolizes the ship's mast and the various ropes used to tie the sail are represented by the canopy glass structure on top of the concert hall and the cable stayed structure on top of the restaurant.

1.1.2 A signature building

The designers anticipated that because of Boston history and location, the ship structure would soon become one of the city's signature buildings. This 30,000 sf elliptical base would sit on a 200, 000 sf green space facing the water. The cable stay structure would remind the viewer of the Zakim Bridge and the canopy glass structure the Eden Project in England. This concert hall would succeed the Fleet Pavilion on the waterfront by virtue of its size and elegance.

1.2 THE STRUCTURE

1.2.1 The concept

The primary concern in this design was the interdependence of the different structural systems.

1.2.2 The different elements

The structure presents four different structural items that work together as an integrated whole:

- The truss box restaurant
- The concert hall steel frame
- The cable-stayed tower
- The glass canopy

Following is a SAP drawing that will help us better understand the importance of the interdependence between the different elements:

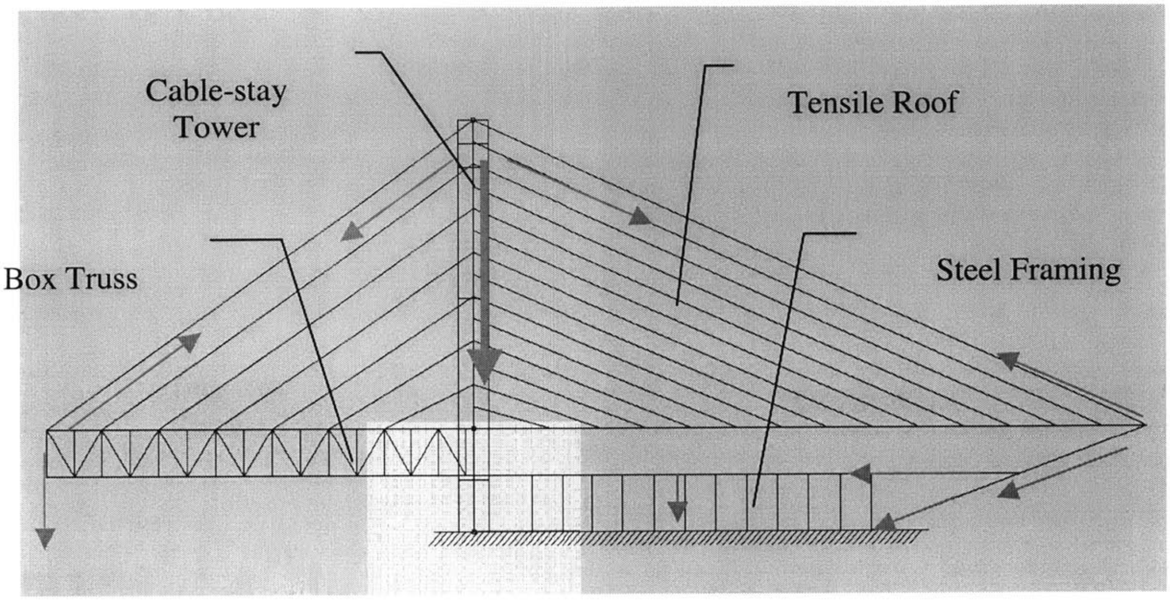


Figure 2: Load Path Schematic

Starting on the left side of the drawing (See Figure 2), the gravity loads of the restaurant are transferred to the cable-stayed system. At the same time, on the right side of the drawing, the gravity loads in the concert hall roof are taken by the tensile roof and act on the tower and the steel frame structure. Both of these actions – tension in the cables and in the canopy – are transferred to the tower. The steel frame acts both as a cantilever for the tensile roof and as a usual load transfer system. Indeed, the gravity loads in the concert hall structure are transferred to the ground by a more commonly used load path: the forces are taken by the second floor, transferred downward via the columns and directed to the foundations.

1.3 THE SITE

The structure is located on Columbus Park. The following rendering shows the site and its surrounding area.[1]

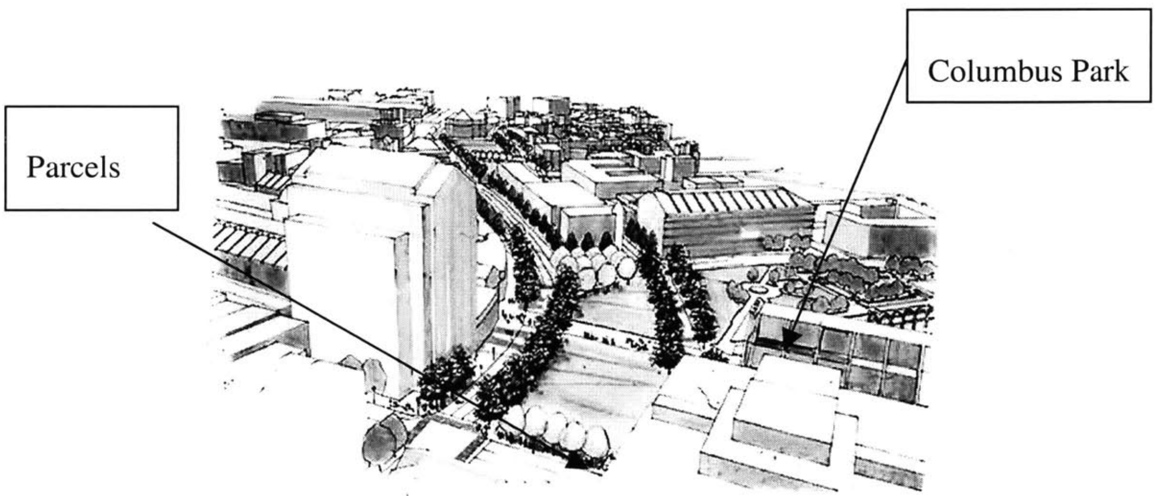


Figure 3: Looking North from Milk Street

1.4 MOTIVATION

From what have been discussed above, the concert hall is clearly a complex structure. This complexity reflects both the design and the structure itself.

The project is complex because the structure itself is designed to be a signature building in Boston. This design implies an expensive structure, with quality materials and workmanship and the use of a skilled labor force. Because the structure is located downtown, near the Boston Aquarium and Quincy Market, the concert hall will be easily visible by the community and Boston's large tourist population. Because the building will house a significant amount of people, fire safety is a strong concern, and demands well-designed fireproofing and fire and smoke detection systems.

The structure adds further complexity to the project. The four structural items listed earlier (the truss box restaurant, the concert hall steel frame, the cable-stayed tower and the glass canopy) are interconnected. This means that each one of them relies on the other to stand. Such interdependence requires a careful and elaborate construction schedule. Access to the site has to be predetermined in advance (by ground or by water) and the pieces of equipment have to arrive in a coordinated fashion. In addition to their interdependence, many structural elements are elaborate in themselves. The glass canopy will require skilled labor to assemble and erect, the steel beams of the shell structure have to be manufactured ahead of time, and the restaurant, as well as the auditorium, have to be fully equipped before the building can open. Erecting such an impressive structure will require high amounts of labor and cannot be accomplished in a reasonable amount of time if a detailed schedule is not in place before construction starts.

The section above has highlighted the need to estimate the schedule of the Boston Harbor Concert Hall. An estimate of project costs must accompany such a schedule in order to estimate the size of the necessary financing and to plan the disbursement of funds to site contractors. Indeed, in a project this size, money and time can be easily wasted because of a poor estimation. This thesis will provide some cost and schedule calculations to evaluate the price of the concert hall and the time required to build it. I will develop a full first rough estimate of the cost of the building and then focus on some items expected to impose particularly high costs. In terms of scheduling, I will give a first estimation of the project length and give a detailed estimate of the interior finishing.

As noted above, there are four main structural items in the building. In this thesis, when I develop a detailed cost breakdown and the detailed schedule, I will only focus on the concert hall and the restaurant. The glass canopy and the cable-stay tower cost and schedule won't be developed in great detail. Part of this choice comes from the fact the auditorium and the restaurant are unconventional commercial buildings that require specific interior finishing. Such elements held greater research interest than limiting myself to the structure construction process. Moreover, RS Means Square Foot Cost and RS Means Building Construction Cost contained very detailed information on the interior items required of a restaurant and auditorium. Finally, attention to these two unconventional buildings offered a good opportunity to discover the complexity of such buildings.

2 ESTIMATING

2.1 THE CONCEPT

Estimating is a technique widely used in construction projects. "The purpose of estimating is to forecast costs required to complete a project in accordance with the contract plans and specifications"[2]. Estimating has great advantages but also has some drawbacks. The preliminary estimate will help in deciding if a project is feasible and is very useful for rapid iterations of design plans. Eventually, estimation will form the basis for a fair-price bid on the part of the owner and for bid prices for contractors.

While essential, there is a risk that estimation will not reflect accurately the true project costs. Changes in productivity and technology can occur over time, and are particularly important components in the costs of a highly innovative structure. For instance, in a revamp/restart project on a chemical plant, pieces of equipment can be discovered along the way and items can turn out to be more difficult to refurbish then expected. In an innovative structure, there are different sorts of unknowns that must be faced, such as components that will require experimenting with innovative construction techniques. The costs extending from these activities can be greatly underestimated if not taken into account.

This thesis uses two main handbooks to estimate the cost and schedule of the Boston Concert Hall:

- RS Means Square Foot Cost: This book gives cost information on the major types of buildings (commercial, industrial, institutional and so on) using the CSI cost breakdown structure.
- RS Means Building Construction Cost Data: This book goes in much more detail than the previous book, giving very detailed information such as the cost of the equipment and material for a very important number of structural or non structural elements.

2.2 COST ESTIMATING

Cost estimating is a critical component of Project Management. The three actors – the owner, the designer and the contractor - involved in a project look for different kinds of cost estimates. The owner's primary concern is to know if he can pay for the project, and how the financing should be arranged. He then needs an approximate cost estimate to select the design, and more detailed cost estimates as the design is finalized. The designer has to be able to calculate the cost of design alternatives and the contractor wants to know how much he will be paid for throughout the project. There are two broad types of estimates:

- Approximate estimate

- Detailed estimate

2.2.1 Approximate estimate

The approximate estimate of a project is typically conducted in the context of a feasibility study and an economic analysis to evaluate his profit/return on investment. In order to derive this estimate, the designer has to evaluate the cost of the project per square foot of floor or cubic meters of concrete. This is a difficult task and requires a lot of experience due to uncertainties with regard to several factors (such as the quality, uncertainties about myriad design details, skill level and productivity of the labor force or the location of the project) that can influence the cost of a structure. This estimate is acceptable to be presented to the owner for the sake of feasibility analysis and a decision to proceed with design development but not to bid. If the owner wants to bid before all the construction documents are issued, the contractor calculates an estimate the best way he can with the information he has and both the owner and the contractor negotiate a reasonable compensation scheme – frequently including some elements of flexibility to reflect the attendant uncertainties. It is clear that this strategy typically requires that both the owner and the contractor have previous experience in the type of project bided.

2.2.2 Detailed estimates

Detailed estimates are prepared for the bidding process and represent the sum of several factors:

- Direct costs (materials, labor and equipment)
- Overhead (indirect cost required to build the project)

- Contingencies (a catch-all cost category to reflect the likely cost of modifications or other risks during construction)
- Profit (to compensate the contractor for the work)

Different steps have to be followed to prepare a detailed estimate[1].

1. Review the scope of the project:

The contractor takes into account the location of the project, the basic design parameters as specified by the owner, the surrounding area in terms of security, traffic and existing above or underground structures. He can do so by visiting the site and gathering information on it.

For the Boston Harbor Concert Hall, the scope of the project was delineated at the beginning of the thesis. The author visited the site and took pictures of the surrounding area, researched information on the internet on accessibility and parking spacing in the area, and obtained information on the transformations the Big Dig impose on nearby roads. This information has not been developed in the thesis because my main focus is on cost and scheduling, and because the components will impact mostly procurement, which is not examined in this thesis. Two important aspects can be mentioned:

[1] R.L. Peurifoy, and G. D. Oberlender (1989) Estimating Construction Costs, *Mc Graw Hill,* Fourth Edition

- The site is downtown: Access to site will have to be carefully planned so that it doesn't interfere with current traffic flow.
- The site is on the water: Access to the site will be possible via water.

Hence, the cost of delivering material would have to be estimated taking into account those two transportation considerations.

2. Determine quantities:

The contractor does a quantity takeoff of all the project items. To do so, he evaluates the quantity of material needed on the project by reviewing all the construction drawings. The takeoff consists of a list of the different items quantity with their units.

For this structure, the drawings available were not detailed enough to generate a detailed take-off but were extremely useful to give basic structure parameters (e.g. perimeters and square footage) of the main parts of the building. This allowed me to use RS Means Square Foot handbook to calculate a lower bound of the building cost.

3. Price material:

Material cost = Quantity*Unit price

This formula will be used throughout the whole cost section.

4. Price labor:

(Quantity/Labor production rate)*Labor rate

Price of labor is already included in RS Means Square Foot Cost and RS Means Building Construction Cost Data, so this formula is only implicitly used.

5. **Price equipment:**

(Quantity/Equipment production rate)*Equipment rate

Price of equipment is also included in RS Means Square Foot Cost and RS Means Building Construction Cost Data, so this formula is again only implicitly used.

6. **Obtain specialty contractor's bid and supplier's bid**

7. **Estimate Overhead costs**

Overhead costs include job overhead costs and general costs. Job overhead costs are specific to a project and refer consists of the salaries, the cost of the utilities, the insurance and so on. The general overhead consists of the cost at the general office such as rent, taxes and so on.

Overhead is included in RS Means Square Foot Cost and RS Means Building Construction Cost Data and will be reflected in the estimates drawn from these sources.

8. **Estimate necessary Contingency**

Contingencies refer to the unknown changes that can occur in a project. For example, in revamp/restart projects, old pieces of equipment can be discovered while installing new pieces of equipment, some items can turn out to be much more time consuming then expected because of their poor condition and so on. Establishing contingency costs is then very difficult but also critical. Indeed, for a contractor underestimating them will reduce the company profit, and overestimating them won't allow the contractor to submit a competitive bid.

Contingency will not be taken into account in the estimate. The estimate that will be developed will then be a lower bound of the actual building cost.

9. Profit

The profit derived by a contractor depends on several factors:

- The project
  - Its type (size, complexity, ...)
  - Its location (number of surrounding construction projects, ...)
- The actors
  - The contractor availability
  - The terms of any financing required by a contractor to carry over between payments by the owner.
  - The competition
- The bid documents (accurate, complete, ...)

The profit commonly varies from approximately from 5% to 30%. A low profit will be chosen for large projects whereas a large profit is seen in small or risky projects.

Profit is included in included in RS Means Square Foot Cost and RS Means Building Construction Cost Data. But if I had to include it, because the project is risky – innovative techniques used, confined site, expensive building - I would choose between 15% and 20% of profit.

2.2.3 Organization of estimates

To prepare an estimate, a project is typically decomposed into different coded categories. In this thesis, we will characterize costs according to the categories specified by the CSI (Construction Specification Institute), which represents a breakdown common for building construction projects

The CSI method divides the project into 16 different categories, categories that are each broken down into 10 to 20 items. This list is useful for the quantity takeoff, the changes in cost or the final cost. Following is the list of the 16 items:

1. General requirement
2. Sitework
3. Concrete
4. Masonry
5. Metals
6. Wood and plastics
7. Thermal and moisture
8. Doors and windows
9. Finishes
10. Specialties

11. Equipment

12. Furnishings

13. Special construction

14. Conveying systems

15. Mechanical

16. Electrical

2.3 SCHEDULING

Projects are difficult to manage. They can have hundreds of different activities that have to be executed in a coordinated fashion so that the design and construction can be finished on time. Scheduling can identify ahead of time the most critical items in a project and save a lot of time later. It reduces the chance of delay and assists in recovering from delay. It can also assist in identifying resource levels required to execute the project in a timely fashion.

2.3.1 Good and poor scheduling

Good scheduling increases the probability of finishing the project on time. Indeed, on a project, the main issue is time. It is critical that the workers are kept busy and that the equipment arrives on time on site. Developing a schedule ahead of time is important for managing the hours available each day and decreasing the risk of having resources and labor idled due to late procurement. Poor schedules can result if one fails to accurately reflect the realities of work in the field, doesn't coordinate the activity or schedules in such a fashion that it doesn't keep the workers active. Such schedules can considerably delay the overall project length and can disadvantage the owner who wants to use the facilities as soon as possible.

2.3.2 *Different actors*

The different actors involved in a construction project react differently when it comes to the use of a schedule. Owners, generally, require a detail schedule. They want to be able to follow the job. Indeed, the schedule can be used on a construction site to make sure the different activities are happening on time. It is also used after the completion of a project to compare the actual activities sequence to the planned succession of tasks. It is useful then to determine who is responsible for the project delays.

On the other hand, a lot of field supervisors are not fond of global project schedules. They don't believe in following them and find the critical path method more burdensome than anything else. They frequently work by making their own short-term schedule in such a fashion as to keep their crews busy within some window of time. This strategy can result in a good management of the site but can also result in situations where long-term needs are not carefully coordinated and where material or equipment won't arrive on time.

2.3.3 *Scheduling limitations*

With the widespread use of computers, schedules are now much easier to generate and you will see construction supervisors carrying their laptops on the sites. To take advantage of schedules, the managers have to understand that schedules are very useful, especially on projects where there is dozens of activities, but they have their limitations.

While necessary for good management of a large project, formal scheduling tools are are not by themselves sufficient for managing schedules on such projects. A good scheduler is one who anticipates, plans for, and actively manages unpredicted or unpredictable situations. For example, bad weather conditions can shut down the site for a few days, discoveries can be made on the site as underground objects are discovered and engineering drawings are changed or construction during construction. Those modifications have to be included in the schedule in the course of the project so that the schedule reflects the ongoing work on the project. Not including such deviations from the planned schedule can be very dangerous. Other downfalls of scheduling come from its rigid use, failure to update the schedule during project changes, or lack of buy-in by key site personnel. A schedule can be established too early in the design phase or discarded later on. In some cases, schedules can remain with the Construction Manager instead of being propagated from him to the owner and contractor site staff.

2.3.4 Different types of schedules

There are two levels of scheduling:

- Definition stage: this is when the engineering schedule is elaborated
- The execution stage: this is when a more detailed schedule is built

Schedules can be distinguished by their orientation. Some schedules are "resource oriented" will other ones are "time oriented". Most scheduling software is time oriented.

In resource oriented schedules, the scheduler wants to make sure the equipment is used at its full capacity at all time. For example, this is critical with the crane on the construction of a tall building. The cranes have to deliver the pieces of equipment on time to the workers on the higher levels so that the pace of the work can be kept.

Time oriented schedules focus on the time progression of the project – particularly on the date on which the project is likely to be completed.

In reality, resources and scheduling are intimately related because the project durations used as the basis of CPM scheduling assume resources will be available while in many cases the availability of the resources depends on the results of that scheduling. This mutual dependency highlights the complexity of generating a schedule. A lot of parameters have to be taken into account as delays for reviewing and approval, procurement, changes, coordination on site and among the designers in the office.

There are different types of schedules:

- Gantt Charts
- Critical Path Method (CPM)

The Gantt Chart schedule is useful in terms of communication but doesn't represent the dependencies between activities and is limited to a simple schedules, with a smaller number of activities.

Once viewed as a novel technique, the CPM schedule is now widely used. Dependencies between activities can be shown. They reflect constraints arising from regulations, physical considerations, safety procedures, environmental limitations, managerial decisions, resource limitations and so on. Through the use of scheduling algorithms, this technique allows identification of the project critical path. The critical path is a sequence of activity that is very sensitive to modifications. Any extension in duration on this path will delay the overall schedule. The other activities have a float which the owner and the contractor perceive differently. The owner pushes the contractors on tight schedules whereas the contractor wants to be flexible.

3 CONCERT HALL COST ESTIMATION[3]

The previous sections provided background on project scheduling and cost estimation. With those techniques in mind, I will now examine the cost of the Boston Harbor Concert Hall.

3.1 AN INNOVATIVE STRUCTURE

Because the structural design is very innovative – the canopy glass roof is used in only a few structures around the world – several assumptions were made to estimate the cost and the schedule of the concert hall. The auditorium is itself a complex structure as well. Numerous pieces of equipment have to be put in place and verified. This includes the HVAC system, the light and audio system, the seats (6500 in this case), electrical systems, acoustic finishing and so on. Such pieces of equipment will have to be considered in the cost, along with the structural items.

3.2 THE TECHNIQUES USED

To estimate the price of the concert hall, I used two different approaches. First, I looked for similar projects and secondly, I used a published source of cost data (RS Means). RS

Means Square Foot Costs enabled me to roughly estimate the cost of the structure. With RS Means Building Construction Cost, I could detail the cost breakdown of major items.

3.2.1 Existing Projects

As the first part of this project, I researched similar structures, in terms of their function – a concert hall - their structure and their architectural features. Five different designs were judged relevant and gave me a range of representative costs:

- New Jersey Performing Arts Center: $80 million
- Milwaukee Art Museum: more than $120 million
- Orange County Performing Arts Center: $200 million
- Kimmel Center for the Performing Arts: $ 265 million
- Walt Disney Concert Hall: $274 million

The current section briefly surveys each of these projects in the order they were enumerated above.

New Jersey Performing Arts Center[4]

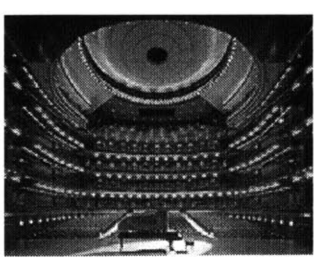
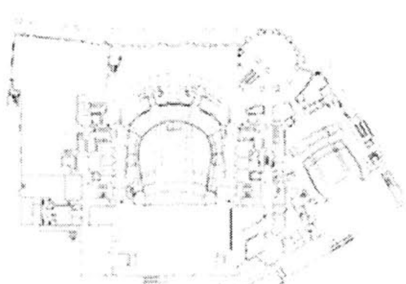
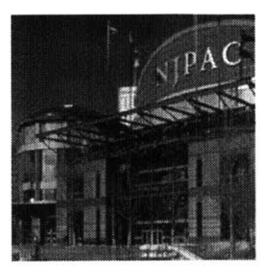
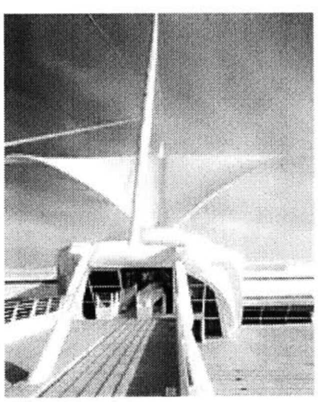




Figure 4: New Jersey Performing Arts Center

Location	Newark, NJ
Client	New Jersey Performing Arts Center
Program	2750-seat Multipurpose Hall, 514-seat Theatre
Architect	Barton Myers Associates
Engineer	Ove Arup and Partners
Subcontractor (Acoustician)	Artec
Building size	250,000 gsf
Completion	1997
Cost	$80 million

The Boston Harbor Concert Hall is almost a duplicate of this smaller Center for Performing Arts in Newark with respect to its purpose and its facilities. New Jersey Performing Arts Center (See Figure 4) was created to revitalize downtown Newark by offering to venues, restaurants, offices and shops to the Newark community. It is located downtown, and has a view on both the town and the Passaic River waterfront.

Milwaukee Art Museum Quadracci Pavilion[5]



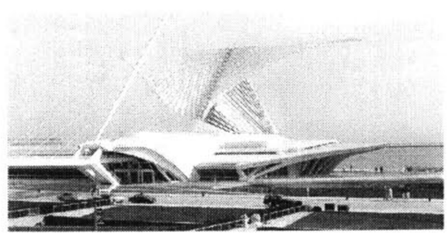


Figure 5: Milwaukee Art Museum Quadracci Pavilion

Location	Milwaukee, WI
Client	Milwaukee Art Museum, Inc.
Program	Museum
Architect	Santiago Calatrava Valls
Engineer	CG Schmidt Construction
Subcontractor (formwork)	PERI GmbH
Building size	Length: 134 m Width: 37 m
Project Construction Time	1994-2001
Cost	More than $120 million

The Milwaukee Art Museum (See Figure 5) is one of the city's signature structures. As for the Boston Harbor Concert Hall, a close reflection was done to make the structure and the architecture evolve together. The result of this effort is a remarkable lakefront birdlike structure made of 72 steel fins resting upon a glass reception hall. The city is linked to the museum by a cable stay pedestrian bridge.

Orange County Performing Arts Center[6]

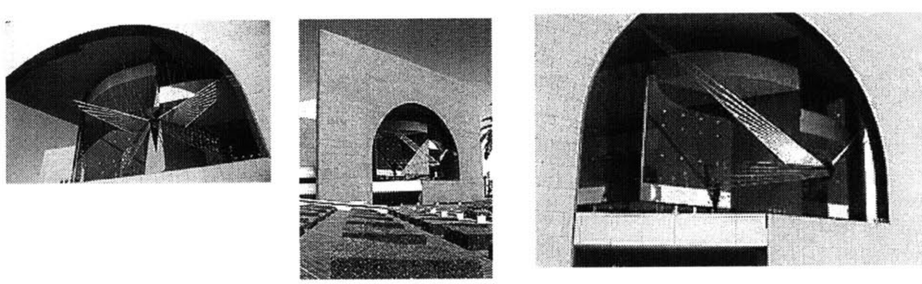


Figure 6: Orange County Performing Arts Center

Location	Costa Mesa, CA
Program	Over 3000-seat
Cost	$200 million

The Orange County Performing Arts Center (See Figure 6) is a massive red granite structure. Located near the megacenter South Coast Plaza, the five story building presents an interesting bird type metallic sculpture flying in the middle of its front arch.

Kimmel Center for the Performing Arts[7]

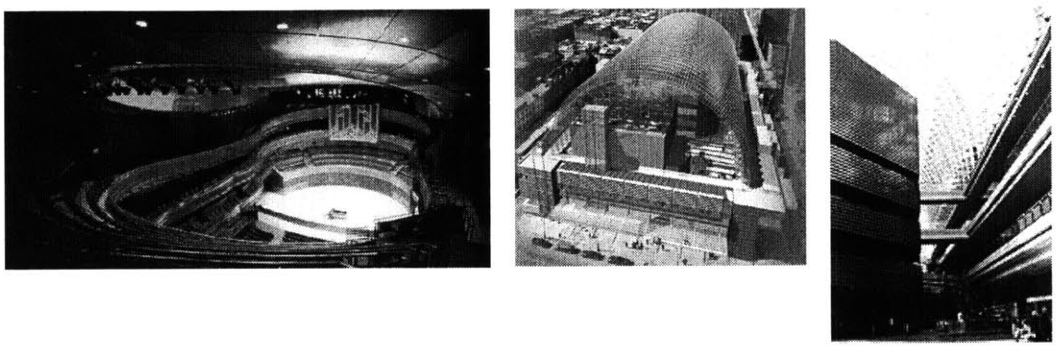


Figure 7: Kimmel Center for the Performing Arts

Location	Philadelphia, PA
Client	**Project Leadership** Willard G. Rouse III, Chairman, RPAC Tom Ridge, Governor of Pennsylvania John Street, Mayor of Philadelphia Edward G. Rendell, former Mayor of Philadelphia
Program	2,500-seat concert hall, *Verizon Hall and* a flexible, 650-seat recital theater, *Perelman Theater*
Architect	Rafael Viñoly, AIA
Engineer	Dewhurst Macfarlane and Partners
Subcontractor (Acoustician)	Russell Johnson, FASA Artec Consultants Inc.
Building size	Footprint: 100,075 sf Gross program area: 429,085 sf
Completion	1998-2001
Cost	$265 million

This project (See Figure 7) also presents similarities with the Boston Harbor Concert Hall. It is meant to be a Philadelphia signature building, the "centerpiece of Philadelphia's Avenue of the Arts". The theaters also present curved and even polygonal exterior glass, steel and brick facades. The building is covered by a giant glass-and-steel barrel vault roof.

Walt Disney Concert Hall[8]

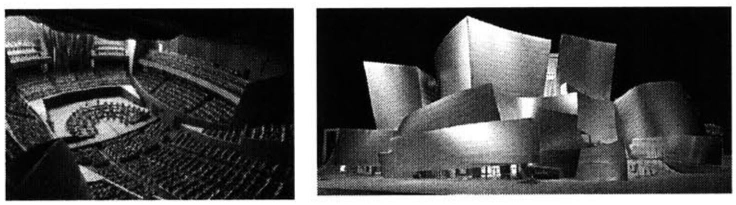


Figure 8: Walt Disney Concert Hall

Location	Los Angeles, CA
Client	Walt Disney Concert Hall Committee
Program	2390-seat Concert Hall
Architect	Frank Owen Gehry
Building size	200,000 square feet
Completion	1999-2002
Cost	$274 million

The Walt Disney Concert Hall (See Figure 8), as the precedent structures, is one of the signature buildings of its host city, "a symbol of renewal for downtown L.A.". It features two outdoor amphitheaters, an indoor theater, an art gallery, a public garden. The concert hall distinguishes itself by its outstanding acoustics.

3.2.2 Harbor building characteristics

To provide a second level of detail into likely project costs, I used the RS Means Square Foot Costs. I chose to focus on the major items of the structure to estimate the concert hall. I considered four major items (See Figure 9):

- The auditorium (term used to refer to the two performance halls)
- The restaurant
- The roof (this includes the glass canopy and the cable-stayed structure)
- The tower

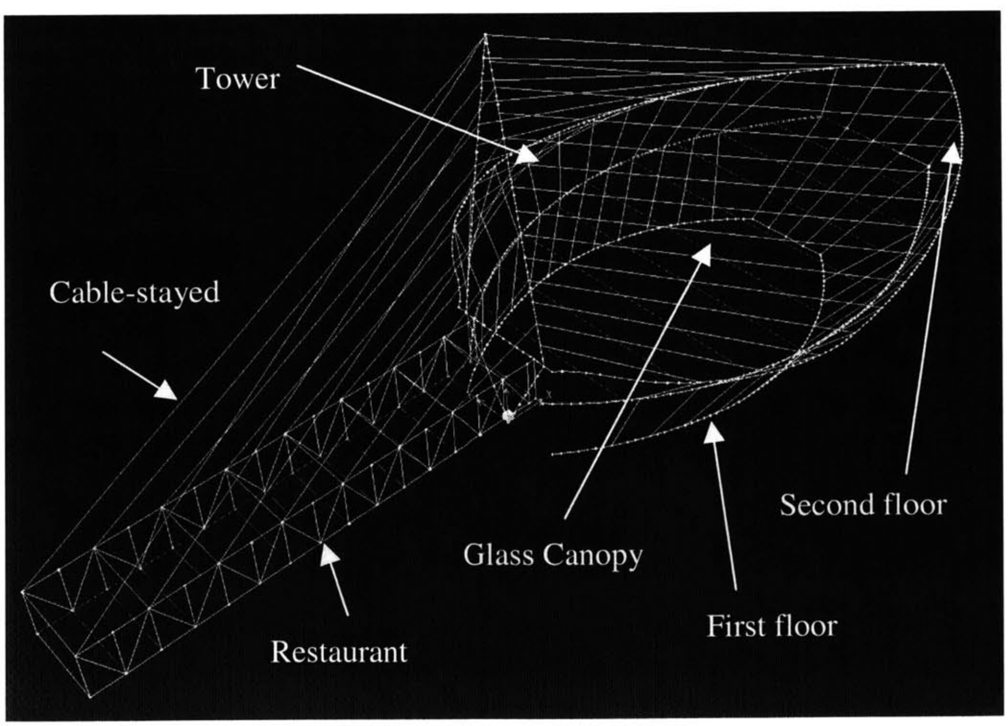


Figure 9: Structure 3D Rendering

Following are the major characteristics of the auditorium, restaurant, canopy and tower. This includes the square footage of each item and the length and weight of particular elements such as the canopy cables or the concrete.

Auditorium characteristics

The auditorium item groups two performance halls. The first one, on the first floor (See Figure 10), is 30,705sf. On top of it is a bigger auditorium (See Figure 11), with a square footage of 46,874. The total height of the two auditoriums is 185 ft.

The bottom auditorium will be a simple flat venue housing 1,500 people. The top one will house 5,000 people and its shape will follow the curvature of the ship, and offers a series of balconies in the back of the performance hall.

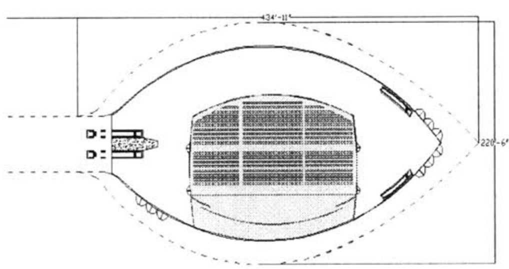


Figure 10: First Floor Auditorium

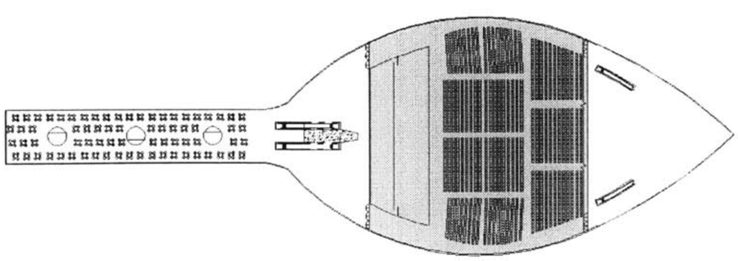


Figure 11: Second Floor Auditorium

Restaurant characteristics

The restaurant will house 1,500 people in a rectangle box truss suspended above water by a cable stay-structure. . It is designed to be an entirely glass structure (surrounded by steel members), so that the customers will actually have a maritime experience while eating. It is a square footage of 12,000 and is 24 ft high. The advantage of having a suspended restaurant is that it will require no earth work.

The kitchen will have to be fully sized and equipped to supply peak customer demand.

Canopy characteristics

The cable-stayed canopy is composed of 14 cables, 200 ft long each. It has 62 longitudinal cables, ranging from 8.5 ft to 477.5ft and 63 lateral cables, ranging from 11 ft to 385 ft, both made of galvanized high-tensile steel. This cable grid is filled with 2885 4" by 8" silicate glass panels, connected to the cables by 11,540 stainless steel clips, thus forming a 92,320sf tent type structure (See Figure 12 and Figure 13).

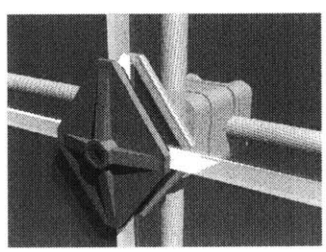


Figure 12: Rendered Image

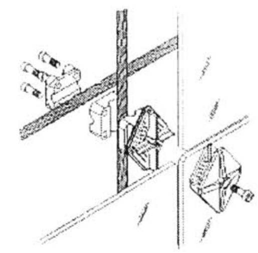


Figure 13: Exploded View

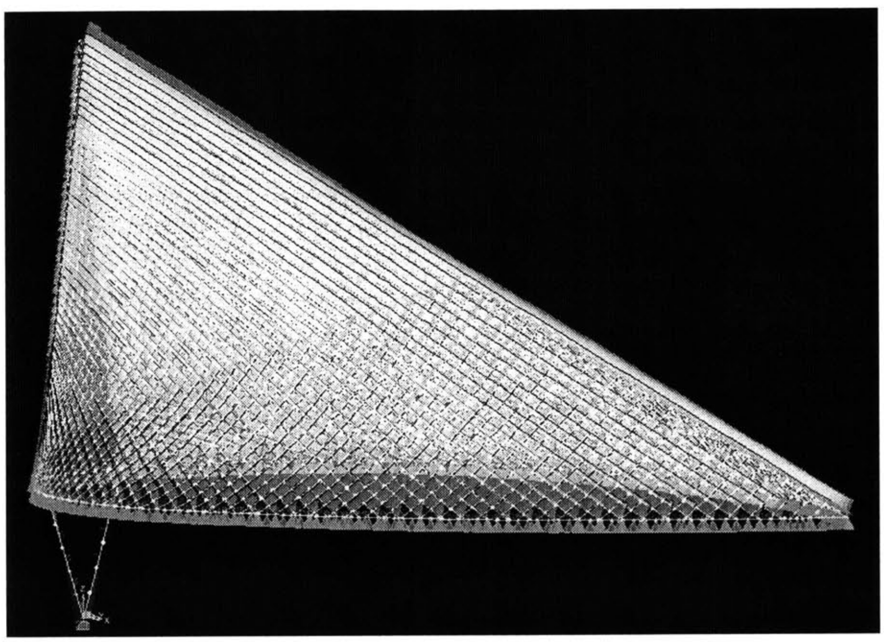


Figure 14: Canopy 3D Rendering

Tower characteristics

The tower is composed of different items, among which are the reinforced steel, the concrete and the pylon. To build the tower, 571,727lb of reinforced steel will be needed, along with 77,786 ft^3 of concrete and 37,812ft^2 of formwork. One pylon is needed.

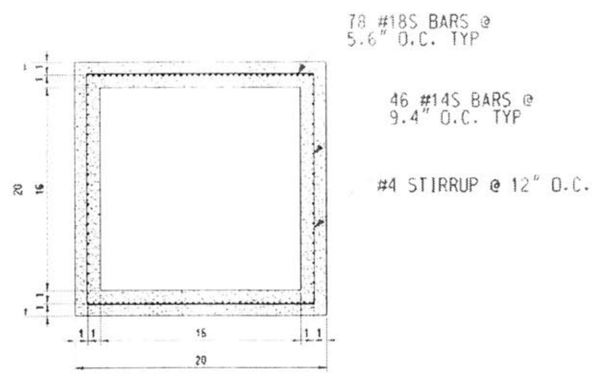


Figure 15: The Tower Cross-Section

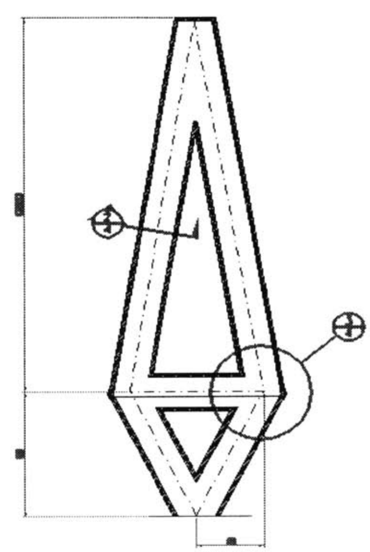


Figure 16: The 262ft High Tower

3.2.3 Boston Harbor Concert Hall cost estimation

The cost estimation of the Boston Harbor Concert Hall was done in two phases.

During the first phase, the cost of the structure was calculated using RS Means Square Foot Costs CSI master format. As noted above, this breaks down the cost of the different items into 16 major activities:

1. General requirement
2. Site work
3. Concrete
4. Masonry
5. Metals
6. Wood and plastics
7. Thermal and moisture
8. Doors and windows
9. Finishes
10. Specialties
11. Equipment
12. Furnishings
13. Special construction
14. Conveying systems
15. Mechanical
16. Electrical

This breakdown helped me to get a first estimate of the structure. This estimate does not take into account the fact that the concert hall is a signature building. Indeed, RS Means Square Foot Cost handbook states: "Costs should be adjusted where necessary for design alternatives and owner's requirements". I then decided to adjust the cost of the structure by calculating an adjustment coefficient using the cost and square footage of some similar structures (See Section 3.2.1). Also, RS Means cost estimates are for conventional structures and not signature buildings as the Boston Concert Hall.

For my second phase of calculations, I considered that the cost of the interior finishing was greatly underestimated in RS Means Square Foot Costs. Indeed, it doesn't take into account special items as seats, special covering and so on. I decided then to subtract this generic interior finishing cost from my total rough cost, recalculate the structure with the adjustment coefficient noted above, and use RS detailed per-component estimates drawn from Means Building Construction Cost Data to calculate the cost of the interior finishing.

This is how it would be in an equation (See Equation 1):

- Total Cost: $TC_{\text{Square Foot Costs}}$
- Interior Finishing Cost: $IFC_{\text{Square Foot Costs}}$
- Adjustment factor: AF
- New Interior Finishing Costs: $NITC_{\text{Building Construction Cost Data}}$
- Final Cost: FC

$$FC = (TC_{\text{Square Foot Costs}} - IFC_{\text{Square Foot Costs}})*AF + NITC_{\text{Building Construction Cost Data}}$$

Equation 1: Final AuditoriumCost Estimation

I could do this completely for the auditorium. Using the adjustment coefficient and recalculating the interior finishing cost increased the estimated cost of the auditorium by a factor of almost ten. I couldn't calculate an adjustment factor for the restaurant because I didn't have existing projects examples on which to draw. But I still subtracted the rough cost of the interior finishing for conventional structures specified by RS Means Square Foot Costs and calculated a more accurate one using RS Means Building Cost Data. For the tower and the canopy, the cost is mainly the cost of material.

The final cost that I will have is a lower bound because:

- The steel work is greatly underestimated
- The interior finishing is roughly estimated, using only partial design details. A full design would very likely specify more extensive furnishings.
- Labor and equipment are almost not taken into account for the canopy and the tower

3.2.4 Auditorium cost estimation

The basics of the auditorium cost estimation were explained in the previous section. I first calculated the cost of the structure with RS Means Square Foot Costs only. This gave me a first extreme lower bound of 6,294,377 dollars. This represented only the costs for a conventional auditorium (such as might be present in a school or library), and requires adjustment to represent the greater technical demands and quality required of a signature building.

In order to derive a sense of the degree of cost inflation associated with signature performance halls, I studied the ratio between the actual structure cost and the cost of a conventional structure with similar overall parameters for several similar structures.

Following are my different steps to calculate the adjustment factor.

For this calculation, I used the information I had available on three similar structures:

- New Jersey Performing Arts Center
- Kimmel Center for the Performing Arts
- Walt Disney Concert Hall

Having their cost and square footage, I calculated their cost per square foot.

	Cost	**SF**	**Cost per SF**
New Jersey Performing Arts Center	80,000,000.00	250,000.00	320.00
Kimmel Center for the Performing Arts	265,000,000.00	429,095.00	617.58
Walt Disney Concert Hall	274,000,000.00	200,000.00	1,370.00

Table 1: Similar Structures Cost per Square Foot

In order to account only for construction costs, I first had to subtract the cost of design from the cost I first computed, RS Means not including the cost of design, but only the contractor and architecture fees. Lacking definitive information on design costs, I erred on the conservative side and assumed that the design would be 10% of the total cost.

With RS Means, I knew that the cost per square feet for a conventional auditorium was $106.04.

I could then compute a ratio of RS Means cost to true structure costs. Taking the average of those ratios, I obtained a default adjustment factor of 6.53 It is worth remarking that there is a high variation in the ratios observed between conventional and signature structures for the performance halls examined.

	Cost per SF	Without Design	Ratio
New Jersey Performing Arts Center	320.00	288.00	2.72
Kimmel Center for the Performing Arts	617.58	555.82	5.24
Walt Disney Concert Hall	1,370.00	1,233.00	11.63
RS Means		106.04	6.53

Table 2: Adjustment Factor

Following is the CSI breakdown for the auditorium, with both numbers provided by RS Means Square Foot Costs and those adjusted by the coefficient estimated above.

	Unit	Unit Cost	Cost per SF	Cost adjusted	Total	Total (Adjusted)
Foundations						
Footings and Foundations	SF Ground	2.44	2.44	15.93	488,000.00	3,186,001.16
Piles and Caissons				0.00	0.00	0.00
Excavation and Backfill	SF Ground	1.08	1.08	7.05	216,000.00	1,410,197.24
Substructure						
Slab on Grade	Sf Slab	3.96	3.96	25.85	184,140.00	1,202,193.14
Special Substructures				0.00	0.00	0.00
Superstructure						
Columns and Beams	SF Floor	0.39	0.39	2.55	30,255.81	197,530.83

Structural walls				0.00	0.00	0.00
Elevated Floors	SF Floor	11.25	1.41	9.21	109,386.39	714,149.93
Roof	SF Roof	5.46	5.46	35.65	504,067.20	3,290,898.94
Stairs	Flight	5,975.00	0.75	0.00	47,800.00	47,800.00
Exterior Closure						
Walls	SF Wall	16.39	8.39	54.78	1,249,480.75	8,157,473.61
Exterior Wall Finishes				0.00	0.00	0.00
Doors	Each	2,527.00	1.27	0.00	30,324.00	30,324.00
Windows and Glazed Walls	SF Window	29.00	3.73	0.00	0.00	0.00
Roofing						
Roof coverings	SF Roof	2.21	2.21	14.43	204,027.20	1,332,030.53
Insulation	SF Roof	1.32	1.32	8.62	121,862.40	795,601.94
Openings and Specialties	SF Roof	0.27	0.27	1.76	24,926.40	162,736.76
Interior Construction						
Partitions	SF Partition	5.90	2.36	15.41	0.00	0.00
Interior Doors	Each	534.00	1.34	534.00	0.00	12,816.00
Wall Finishes	SF Surface	2.38	1.90	12.40	56,316.00	367,669.76
Floors Finishes	SF Floor	7.00	7.00	45.70	543,053.00	3,545,425.18
Ceiling Finishes	Sf Floor	2.69	2.69	17.56	208,687.51	1,362,456.25
Interior Surface/Exterior Wall	SF Wall	2.12	1.09	7.12	32,307.60	210,926.33
Conveying						
Elevators	Each	57,120.00	2.38	0.00	228,480.00	228,480.00
Special Conveyors				0.00	0.00	0.00
Mechanical						
Plumbing	Each	2,936.00	3.67	0.00	58,720.00	58,720.00
Fire Protection	SF Floor	1.69	1.69	11.03	131,108.51	855,966.94
Heating				0.00	0.00	0.00
Cooling	SF Floor	10.95	10.95	71.49	849,490.05	5,546,057.96
Special Systems				0.00	0.00	0.00
Electrical						
Service and Distribution	SF Floor	1.44	1.44	9.40	111,713.76	729,344.61
Lighting and Power	SF Floor	7.89	7.86	51.32	609,770.94	3,981,005.99
Special Electrical	SF Floor	3.28	3.28	21.41	254,459.12	1,661,284.94
Special Construction						
Specialties				0.00	0.00	0.00
Site work						
Earthwork				0.00	0.00	0.00
Utilities				0.00	0.00	0.00
Roads and Parking				0.00	0.00	0.00
Site Improvements				0.00	0.00	0.00
Total			80.33	972.66	6,294,376.64	39,087,092.05

Table 3: Auditorium CSI Breakdown

The cost of the auditorium with the adjustment factor is estimated above as 6 times greater then the first estimate.

The estimates above include only a rough breakdown of the interior items for the design. Because the design includes specification of a large number of expensive items got for the interior work, I then decided to make a more detailed the cost estimate of the interior finishing using RS Means Building Construction Cost Data.

In order to start with an estimated cost for the non-interior construction, I subtracted the cost of the "conventional" interior finishing from the total construction estimate:

Total	39,087,092.05
Interior Finishing	5,499,293.52
Cost without Interior Finishing	33,587,798.53

Table 4: Cost without Interior Finishing

RS Means Building Construction Cost Data has cost breakdowns for Auditorium items and Stage equipment. Based on this, I could then estimate much more accurately the cost of the interior finishing. Following is the cost breakdown I obtained, knowing that the total number of seats is 6,500 and the total stage area is 15,768:

	Unit	Unit	Total Incl O&P	Total
Auditorium Items				
Emergency Ligthing, 25 watt, battery operated				
Nickel cadmium	Each	100.00	655.00	65,500.00
Seating				
Auditorium chair, all veneer	Each	6,500.00	166.00	1,079,000.00

Smoke detectors				
Ceiling type	Each	100.00	149.00	14,900.00
Sound System				
Amplifier, 250 watts Speaker, ceiling or wall	Each	100.00	145.00	14,500.00
Stage Equipment				
Control boards with dimmers and breakers, max	Each	100.00	79,000.00	7,900,000.00
Curtain track, straight, heavy duty	LF	322.00	82.00	26,404.00
Silica based yarn, fireproof	SF	15,768.00	28.00	441,504.00
Cart to carry 225 SF of flooring lights, border, quartz, reflector, vented	Each	100.00	335.00	33,500.00
Strobe light, 1 to 15 flashes per second, quartz	Each	100.00	730.00	73,000.00
Telescoping platforms, extruded alum., straight, pie-shaped, max	SF Stg.	700.00	65.50	45,850.00
Chair for above, self-storing, max	Each	100.00	155.00	15,500.00
Rule of thumb: total equipment, max	SF Stg.	15,768.00	500.00	7,884,000.00
Total				9,709,658.00
Other items	Unit	Unit	Cost	Total
Interior cladding (auditorium wood panels)	SF	148,925.00	4.13	615,060.25
Carpenting	SF	77,579.00	8.31	644,681.49
Acoustical treatment (auditorium)	SF	148,925.00	13.35	1,988,148.75
Exterior cladding (audiorium ceramic panels)	SF	148,925.00	10.70	1,593,497.50
Toilets	Each	76.00	1,175.00	89,300.00
Total				4,930,687.99

Table 5: Cost Breakdown for Auditorium Additional Items

The design did not specify the quantity of material needed in an auditorium. RS Means Building Construction Cost Data gave rough estimates for the cost of the stage equipment. With this indication, I could come to a close estimation of the amount of material needed. Those amounts are then not completely accurate but not including them would be worse than overestimating them. I then decided on an arbitrary amount of equipment needed (100 here) to take them into account. These pieces of equipment include but are not limited to smoke detectors, speaker, carts and so on.

The final estimate for the cost of the two auditoriums is then $46,675,435:

Structural cost	33,587,798.53
Interior cost	14,640,345.99
Total	48,228,144.52

Table 6: Total Auditorium Cost

This cost is 7.7 greater than the original estimation. Itemizing the interior finishing costs elevated the cost for these items $5,499,294 to $14,640,346 – a factor of 2.7 greater than the first cost estimated with RS Means Square Foot Costs. Also, the ratio of the interior finishing over the structural estimated costs is significant: 44% of the cost is just interior finishing.

3.2.5 Restaurant cost estimation

The restaurant cost estimation, followed the same general procedure as for the auditorium, with the exception of the fact that no adjustment coefficient was derived or applied.

My first estimation, not taking into account the special restaurant interior furnishing, is the following:

	Unit	Building data	Unit Cost	Cost per SF	Total
Foundations					
Footings and Foundations	SF Ground	0.00	4.73	4.73	0.00
Piles and Caissons					
Excavation and Backfill	SF Ground	0.00	1.28	1.28	0.00
Substructure					

Slab on Grade	Sf Slab	0.00	3.32	3.32	0.00
Special Substructures					
Superstructure					
Columns and Beams	SF Floor	12,000.00	0.34	0.85	10,200.00
Structural walls					
Elevated Floors					
Roof	SF Roof	12,000.00	4.88	5.46	65,520.00
Stairs	Flight	0.00			0.00
Exterior Closure					
Walls	SF Wall	13,920.00	7.82	3.94	54,844.80
Exterior Wall Finishes					
Doors	Each	0.00	3,185.00	3.19	0.00
Windows and Glazed Walls	SF Window	10.00	29.00	6.29	62.90
Roofing					
Roof coverings	SF Roof	12,000.00	3.28	3.67	44,040.00
Insulation	SF Roof	12,000.00	1.00	1.12	13,440.00
Openings and Specialties	SF Roof	12,000.00	0.52	0.52	6,240.00
Interior Construction					
Partitions	Sf Partition	4,640.00	730.00	1.92	8,908.80
Interior Doors	Each	10.00	384.00	1.54	3,840.00
Wall Finishes	SF Surface	4,640.00	1.79	1.43	6,635.20
Floors Finishes	SF Floor	12,000.00	6.15	6.15	73,800.00
Ceiling Finishes	Sf Floor	12,000.00	3.63	3.63	43,560.00
Interior Surface/Exterior Wall	SF Wall	4,640.00	3.08	1.55	7,192.00
Conveying					
Elevators	Each	0.00			0.00
Special Conveyors					
Mechanical					
Plumbing	Each	10.00	2,825.00	7.96	28,250.00
Fire Protection	SF Floor	12,000.00	1.69	1.69	20,280.00
Heating					
Cooling	SF Floor	12,000.00	25.00	25.10	301,200.00
Special Systems					
Electrical					
Service and Distribution	SF Floor	12,000.00	2.76	2.76	33,120.00
Lighting and Power	SF Floor	12,000.00	6.64	6.64	79,680.00
Special Electrical	SF Floor	12,000.00	0.66	0.66	7,920.00
Special Construction					
Specialties					
Site work					
Eartwork					
Utilities					0.00
Roads and Parking					0.00
Site Improvements					0.00
Total				95.40	808,733.70

Table 7: Restaurant CSI Breakdown

In a manner similar to that used for the auditoriums, I then estimated the cost of the interior finishing with RS Means Building Cost Data. Because the design does not specify detailed lists of the equipment required for the kitchen, there was a need to seek professional guidance on deriving these data. For this purpose I consulted with a professional in the food service industry[9]. He gave me the basic layout for a 300 people restaurant (See Figure 17: Layout of Restaurant).

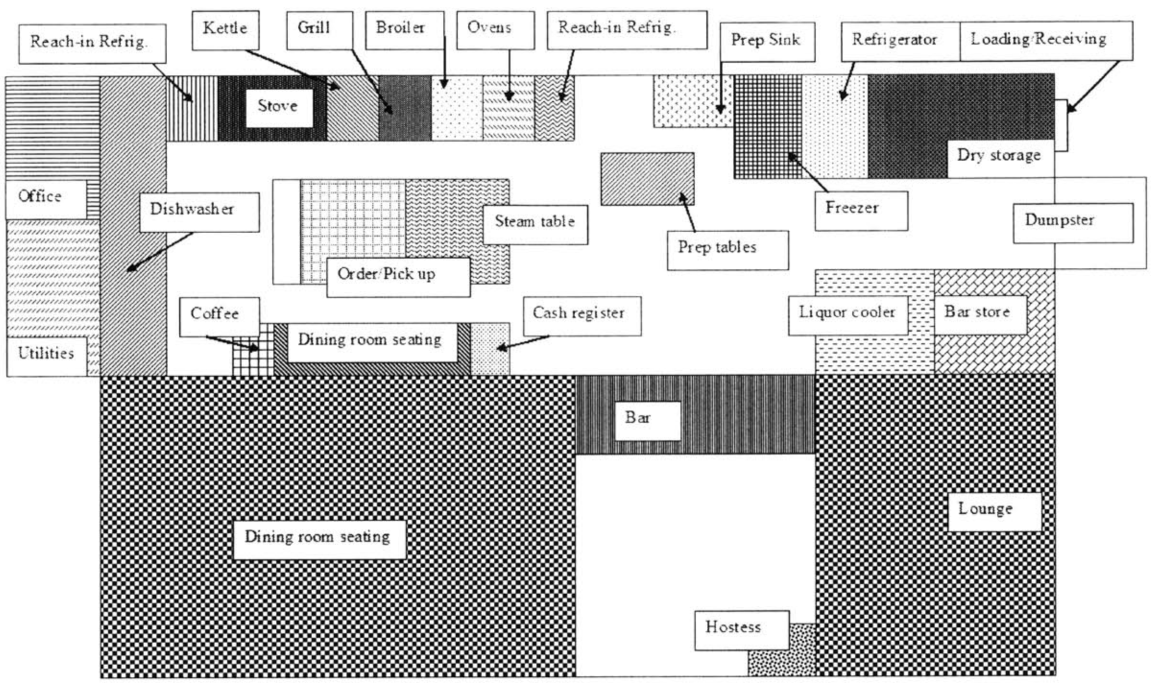


Figure 17: Layout of Restaurant

Because each item is needed once in the kitchen (oven, dishwasher, etc) for a 300 people restaurant and because the Boston Harbor Concert Hall restaurant total capacity is 1500 people, I linearly scaled the equipment count by a factor of 5 when choosing the number of items required in the kitchen of the Boston Harbor Concert Hall.

Description	Unit	Building data	Cost	Total
Bar				
Front bar	LF	30.00	285.00	8,550.00
Back bar	LF	30.00	227.00	6,810.00
Emergency lighting, 25 watt, battery operated				
Nickel cadmium	Each	10.00	655.00	6,550.00
Kitchen equipment				
Broiler	Each	5.00	4,050.00	20,250.00
Coffee urn, twin 6 gallon	Each	5.00	6,975.00	34,875.00
Cooler, 6 ft, long	Each	5.00	3,200.00	16,000.00
Dishwasher, 10-12 racks per hr	Each	5.00	3,050.00	15,250.00
Food warmer, counter, 1.2 KW	Each	5.00	715.00	3,575.00
Freezer, 44 C.F., reach-in	Each	5.00	8,325.00	41,625.00
Ice cube maker, 50 lb. per day	Each	5.00	1,800.00	9,000.00
Range with 1 oven	Each	5.00	2,400.00	12,000.00
Refrigerators, Prefabricated, walk-in				
12'*20'	SF	12,000.00	73.00	876,000.00
Total				1,050,485.00
Additional items				
Chairs and tables	Unit	Unit	Cost	Total
Chairs	Each	1,500.00	95.50	143,250.00
Tables	Each	1,500.00	1,500.00	2,250,000.00
Electronic				
PC	Each	5.00	2,000.00	10,000.00
Software	Each	5.00	8,000.00	40,000.00
Glass floor (restaurant)	SF	12,000.00	1158.00	1,380,000.00
Total				3,823,250.00

Table 8: Cost breakdown for Restaurant Additional Items

On the basis of the above, a conservative estimate for cost of the restaurant is then the following:

Structural total	823,766.80
Interior finishing	4,873,735.00
Final Restaurant cost	5,697,501.80

Table 9: Total Restaurant Cost

I believe that this estimate represents a lower bound on the cost of the restaurant. Indeed, only the glass floor was taken into account but the box truss was not closely estimated. It was just assumed to be counted in the "Superstructure" CSI category under "Columns and beams" when the structure is actually a steel box truss system.

3.2.6 Other items cost estimation

Sections above have provided estimates for two important components of the structure: The auditorium and restaurant. The two items remaining are the canopy and the tower. I included the cost of the cable-stay cables in the canopy cost estimation.

- Canopy and cable-stay cost[10]

Number of cables	Type of cable	Unit	Length	Building data	Unit cost	Total
Restaurant side		LF	200.00	14.00	0.50	1,400.00
Concert hall side	Lateral cables	LF	198.00	62.00	0.95	11,662.20
galvanised high-tensile steel	Longitudinal cables	LF	243.00	63.00	0.95	14,543.55
Glass	Type of glass					
Concert hall side	silicate glass (4*8)	Each		2,885.00	213.00	614,505.00
Connections						
Concert hall side	stainless steel clips	Each		11,540.00	10.00	115,400.00
Total						757,510.75

Table 10: Canopy Cost

In this cost breakdown, only the cost of the cables, glass panels and connections is considered. The cost of labor and equipment is greatly underestimated because RS Means Building Construction Cost Data assumes simple structures. This is not the case here, the glass canopy being a very innovative structure. The workers will have to install the structure being almost 300 feet above the ground. This estimate is then a lower bound.

- Tower cost[11]

Element/Operation	Unit	Building data	Cost ($)[2]	Cost ($)	Average cost	Total
Reinf. Steel	lb	571,727.03	0.45	0.57	0.51	291,580.78
Concrete	ft^3	77,785.99	3.96	5.02	4.49	349,259.10
Formwork	ft^2	37,812.63	1.02	1.29	1.16	43,673.59
Pylon		1.00	60,397.00	76,626.16	68,511.58	68,511.58
Total						753,025.05

Table 11: Tower Cost

The same comments for the glass canopy are applicable to the tower. Concrete for the tower will have to be poured continually, what implies the use of very special pieces of equipment.

3.2.7 Final cost

On the basis of the cost estimates above, the final cost of the structure could be computed. The following is the data I could compute so far:

---

[2] Pollallis, Spiro. (converted units)

Auditorium	46.675.434.52
Restaurant	5.733.501.80
Canopy	757.510.75
Tower	753.025.05

Table 12: Partial Costs

I had to add the Contractor and Architecture fees.

- Auditorium additional fees

	Cost Per S.F.	Adjusted	Cost
RS Means cost per SF	80.33	972.66	39,087,092.05
Contractors fees (General Requirements: 10%, Overhead: 5%, Profit: 10%): 25%	20.08	243.17	18,864,550.71
Architect fees: 7%	5.62	68.09	5,282,074.20

Table 13: Auditorium Additional Fees

- Restaurant additional fees

	Cost Per S.F.	Cost
RS Means cost per SF	95.40	823,766.80
Contractors fees (General Requirements: 10%,	23.85	286,200.00

Overhead: 5%, Profit: 10%): 25%			
Architect fees: 7%		6.68	80,136.00

Table 14: Restaurant Additional Fees

Also, "cost shown in Mean cost data publications are based on National Averages for materials and installation. To adjust the costs to a specific location, simply multiply the base cost by the factor for that city."[3] Boston coefficient is 1.15. Finally, I had to add the cost of Engineering, which is assumed to be 10% of the final cost.

Auditorium	46,675,434.52
Restaurant	5,733,501.80
Canopy	757,510.75
Tower	753,025.05
Contractor fees	19,150,750.71
Architect fees	5,362,210.20
Boston Coefficient	1.15
Partial total	90,197,297.99
Engineering	9,019,729.80
Final	99,217,027.78

Table 15: Concert Hall Cost

[3] RS Means Company (2000) RS Means Square Foot Costs, *RS Means*, 22nd Annual Edition

The final estimate for the cost of the structure is then 99,217,028 dollars. This cost is a reasonable lower bound for the structure, knowing that the similar structures costs were ranging from 80 million dollars to 274 million dollars and knowing that some items were not taken into account in the cost calculation. Those items include:

- The steel work
- The interior finishing
- Labor and equipment for the canopy and the tower

4 CONCERT HALL SCHEDULE

The previous chapter described the cost estimation for the concert hall. This chapter turns to focus on the derivation of the schedule for that structure. As for the concert hall cost, I established the concert hall schedule in different steps, going from an initial rough estimate to a more detailed one.

For the initial approximate estimate, I first identified the major activities. Using a rough estimate of the productivity for each activity, I then derived an upper bound for the construction time length. For the detailed estimate, I chose to focus on some particular items, drawing productivity estimates from RS Means Building Construction Cost Data. Using this technique could break down some major activities using the daily-output and labor hours given for each piece of equipment.

It is important to note that the schedule formulated only accounts for steps in the on-site construction process. As such, it ignores other time-critical activities that must be carefully coordinated with the construction process, such as procurement. The innovative nature of the concert hall design and its heavy reliance on steel design makes it likely that there will be a lengthy procurement process for many site components.

4.1 THE FIRST ESTIMATE

Consulting with members of the design team, I divided the work into 15 major construction activities:

1. Site preparation
2. Driving piles
3. Construction of cable-stay
4. Placement of piles caps
5. Slab on grade construction
6. Erection of columns and second floor framing
7. Construction of composite deck
8. Attachment of shell elements
9. Assembly of restaurant truss
10. Hanging of restaurant truss
11. Installation of cable net
12. Installation of roof glass
13. Interior finishing
14. HVAC, electrical, and plumbing installation
15. Exterior cladding

Based on this rough breakdown, I then calculated an approximate amount of time to finish each activity with the following production rates:

Activity	Production rate	Duration (months)
Site preparation	Assumed	2
Driving piles	5 piles/day	3
Construction of cable-stay	1.5 weeks/10 ft lift	10
Placement of piles caps	2-3 pile caps/day/crew	1
Slab on grade construction	10000ft^2/day/crew	1
Erection of columns and second floor framing	1 member/hr/crew	3
Construction of composite deck	Assumed	1
Attachment of shell elements	3 elements/day	2
Assembly of restaurant truss	Assumed	2
Hanging of restaurant truss	1 cable/day/crew	2
Installation of cable net	1 cable/day/crew	2
Installation of roof glass	2 panels/hr/crew	2
Interior finishing	Assumed	8
HVAC, electrical, and plumbing installation	Assumed	3
Exterior cladding	Assumed	5

Table 16: Production Rates

Production rates -- the number of units of work performed by a unit of equipment or a person in a unit of time -- are essential to determine the time an activity will take on a project. Those rates depend on many different factors such as the job complexity, the management conditions and the equipment conditions. These rates can be found in tables.[12]

In the context of this thesis, data was collected from the previous project on which three students and I were working. MIT Lecturer Lisa Grebner could inform us of most of the production rates found above. One of the teammates had some previous experience in construction and estimated the remaining production rates based on the knowledge she gained on construction sites. The Primavera scheduling package was used to create a Critical Path Method schedule using the aggregate activities specified above (See Figure 18). For the purpose of this thesis, I assumed that the construction will start in late

December 2003. The construction of the Boston Harbor Concert Hall will then take 20 months and finish in Early September 2005.

The durations for the aggregate activities specified suggested a total project duration estimate of 20 months. The completion time of the projects described in a previous section included the whole construction of the project and clustered around three years. The estimated project length for the Boston Harbor Concert Hall based on these aggregate estimates is then within a reasonable range.

Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish
01DEC03						
1	Site Preparation	8	8	0	29DEC03	22FEB04
29DEC03						
2	Driving Piles	12	12	0	26JAN04	18APR04
26JAN04						
3	Construction of Cabe-Stay	40	40	0	23FEB04	28NOV04
01MAR04						
4	Placement of Piles Caps	4	4	0	22MAR04	18APR04
29MAR04						
5	Slab on Grade Construction	4	4	0	19APR04	16MAY04
6	Erection of Columns and	12	12	0	19APR04	11JUL04
28JUN04						
7	Construction of Composite	4	4	0	12JUL04	08AUG04
27SEP04						
9	Assembly of restaurant Truss	8	8	0	04OCT04	28NOV04
01NOV04						
10	Hanging of Restaurant Truss	4	4	0	29NOV04	26DEC04
8	Attachment of Shell Elements	8	8	0	29NOV04	23JAN05
27DEC04						
11	Installation of Cable Net	8	8	0	24JAN05	20MAR05
13	Interior Finishing	32	32	0	24JAN05	04SEP05
15	Exterior Cladding	20	20	0	24JAN05	12JUN05
31JAN05						
14	HVAC, Electrical, and Plumbing	12	12	0	21FEB05	15MAY05
28FEB05						
12	Installation of Roof Glass	8	8	0	21MAR05	15MAY05

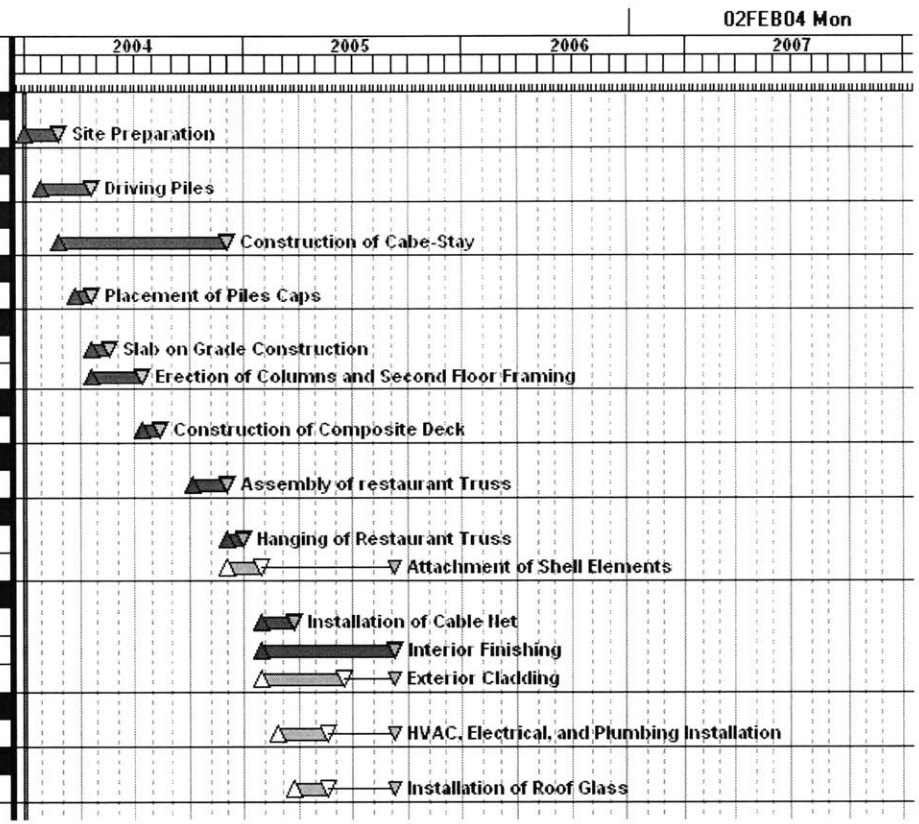


Figure 18: Concert Hall Schedule

Primavera's scheduling algorithm identified the critical path for the project. The critical path includes the site preparation, driving the piles, the construction of the tower, the placement of the piles caps, the slab on grade construction, the erection of columns and second floor framing, the construction of the composite deck, the assembly of the restaurant truss, the hanging of the restaurant truss, the installation of the cable net and the interior finishing. The most time consuming activities are the construction of the cable-stay and the interior finishing. This was expected because:

- The whole structural system relies on the tower
- As the building is composed of two auditoriums and a large restaurant, furnishing them and getting the concert hall ready for visitors will be a detail-intensive and time-consuming work.

4.1.1 The auditorium

Structurally, the construction of the auditorium is relatively standard. As a steel shell structure, the fabrication will be done before construction starts. While this necessitates a long procurement time, this will save considerable site time and will allow for tighter construction tolerances than would be possible with a field erected structures (such as those made of cast-in-place concrete). Most of the connections are bolt connection, except the connection of the second floor to the truss shell structure, which are welded. Such bolted connections require less labor to assemble than if they were welded, permitting a faster assembly.

The construction of the shell is also constrained by the construction of the tower, as well as the erection of the second floor.

4.1.2 The restaurant

As the restaurant is also a steel structure, the manufacturing and fabrication of the trusses will take place off site. The trusses will then be shipped to the construction site.

The construction of the restaurant trusses will take place on the barges, while the tower is erected. Once the tower is built, the restaurant trusses can be hung, one section at a time. Having installed the steel structure, the glass floor, walls and roof of the restaurant will be constructed. The finishing of the restaurant will consist of fully equipping the kitchen with the appropriate machines and putting in place the exterior cladding. A more detailed breakdown of the restaurant interior finishing will be explored in the next section.

4.1.3 Critique

From the previous discussion and from the Primavera bar chart, one can recognize that the construction of the concert hall will be a complex task. The need for a detailed schedule appears to be critical and good management and coordination of the different activities is essential in such construction, in order to deliver the building in a reasonable amount of time.

Additional complications in the construction process will come from the construction site location and size, and from the logistics of materials transport and coordination of the cranes involved in erection. While cranes are needed to transport the steel elements and then glass panels to their appropriate location on the construction site, the site's downtown location limits accessibility to the building for transportation of procured materials and imposes constraints on the the space for storage of such materials. Clearing of the streets at specific times of the day will have to be carefully planned in order to receive material easily.

On the other hand, the coastal location does provide some benefits. The proximity of the site to the harbor will allow workers to install a barge on the shore and thus expand the construction space. Some pieces of equipment will be received via water as well. At the same time, the close proximity to the harbor will constrain the movement of larger mobile pieces of equipment on the site.

As noted above, having a steel structure will allow the manufacturing facilities to begin fabrication of the steel elements before construction starts. This will fit well into the construction schedule because the arrival such pieces of equipment can be roughly coordinated with the progression of the construction process, although some off-site storage will likely be required to lower risk of delays. Even after foundations are in place, the erection of the tower will be the main concern, and needs to be started first, leaving some time to the steel suppliers to finish the manufacturing and fabrication of the restaurant truss and shell elements. Such elements will be needed on site 9 months after construction starts. Having four definite loci of activity also simplifies the construction sequence. Work can be started on the concert hall and the tower while the steel trusses are assembled on the barges. Different crews will have to be coordinated on the site, but if this coordination is well prepared, the work on the site can be very productive.

4.2 DETAILED SCHEDULE

As is typical for building construction, one of the activities on the critical path is the finishing of the interior. As noted in previous chapters, RS Means Building Construction Cost Data provides detailed breakdown of the auditorium and restaurant interior items, with their labor-hours and daily output. Based on this, I decided to calculate the time it will take to equip the interiors of the two auditoriums and the restaurant with major items.

4.2.1 Auditorium detailed estimate

A first estimate was done, assuming the activities were not done in parallel. This assumption was abandoned because while it had the advantage of allowing the work to be done by a smaller set of people, the auditorium alone required 20 months to equip—too long to realistically contemplate.

A second estimate was formulated using the Primavera scheduling package. The goal in this second estimate was to allow activities to proceed concurrently as much as possible. To include this constraint in the schedule, I used the start to start relationship, with a zero time float. The critical path of the auditorium construction appeared to be the installation of the seats. Indeed, because 6,500 seats have to be arranged in the theater and because it takes 45 minutes to put in place each seat, the entire set of work requires close to 5,000 person-hours. I then chose to have two crews working in parallel. This significantly diminished the time to furnish the auditorium. Fireproofing was also an issue. The estimate includes the use of three crews for that purpose as well. I had to put several crews also to finish the interior cladding and carpeting. By using concurrency in this fashion, the auditorium can then be ready in 8 months. Following is the information provided by RS Means (See Table 17) and the final Primavera Bar Chart generated from it (See Figure 19):

	Crew	Daily output	Labor-hours	Unit	Building data	Total labor-hours	Total crew days
Auditorium Items							
Emergency Ligthing, 25 watt, battery operated							
Nickel cadmium	1 Elec	4.00	2.00	Each	100.00	200.00	25.00
Seating							
Auditorium chair, all veneer	2 Carp	22.00	0.73	Each	6500.00	4725.50	295.45
Smoke detectors							
Ceiling type	1 Elec	6.20	1.29	Each	100.00	129.00	16.13
Sound System							
Speaker, ceiling or wall	1 Elec	8.00	1.00	Each	100.00	100.00	12.50
Stage Equipment							
Control boards with dimmers and breakers, max	1 Elec	0.20	40.00	Each	100.00	4000.00	500.00
Curtain track, straight, heavy duty	2 Carp	18.00	0.89	LF	322.00	286.26	17.89
Silica based yarn, fireproof	2 Carp	50.00	0.32	SF	15768.00	5045.76	315.36
Cart to carry 225 SF of flooring lights, border, quartz, reflector, vented	2 Carp			Each	100.00		
Strobe light, 1 to 15 flashes per second, quartz	1 Elec	3.00	2.67	Each	100.00	266.70	33.33
Telescoping platforms, extruded alum., straight, pie-shaped, max	4 Carp	70.00	0.46	SF Stg.	700.00	319.90	10.00
Chair for above, self-storing, max	2 Carp	40.00	0.40	Each	100.00	40.00	2.50
Rule of thumb: total equipment, max	4 Carp	25.00	1.28	SF Stg.	15768.00	20183.04	630.72
Other items				Unit	Unit		
Interior cladding (auditorium wood	2 Carp	400.00	0.04	SF	148925.00	5957.00	372.31

panels)							
Carpeting	1 Tilf	8.33	0.01	SF	77579.00	922.33	9309.48
Acoustical treatment (auditorium)	1 Carp	100.00	0.08	SF	148925.00	11914.00	1489.25
Toilets	2 Marb	3.00	5.33	Each	76.00	405.08	25.33
Total						54494.57	13055.26

Table 17: RS Means Auditorium Total Crew Days Estimation

25AUG05

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish
Chairs					
2	Chairs	148	148	07FEB05	31AUG05
Control					
5	Control boards	125	125	07FEB05	29JUL05
3	Smoke detectors	17	17	01AUG05	23AUG05
Electricity					
1	Nickel Cadmium	25	25	07FEB05	11MAR05
4	Speaker	13	13	07FEB05	23FEB05
8	Strobe light	34	34	07FEB05	24MAR05
Fireproof					
7	Fireproof	106	106	21FEB05	18JUL05
Stage					
9	Platform	10	10	07FEB05	18FEB05
6	Curtain	18	18	19JUL05	11AUG05
10	Chairs for above	3	3	19JUL05	21JUL05
Surfaces					
13	Acoustical treatment	149	149	07FEB05	01SEP05
12	Carpenting	144	144	07FEB05	25AUG05
11	Interior cladding	94	94	21MAR05	28JUL05
Toilets					
15	Toilets	26	26	07FEB05	14MAR05

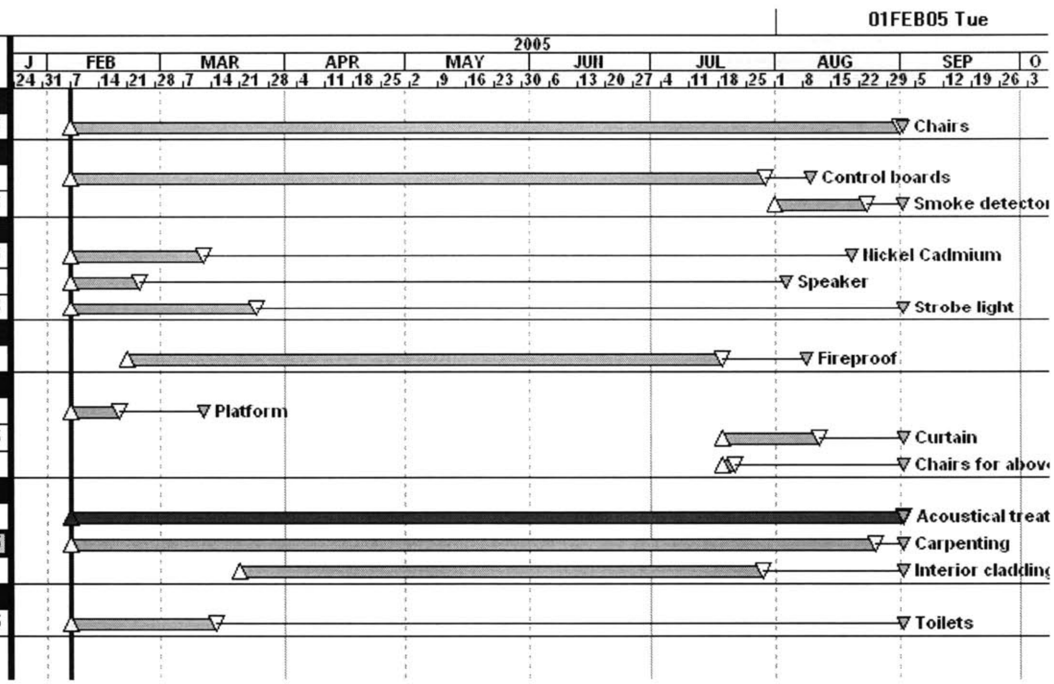


Figure 19: Auditorium Interior Finishing Schedule

One has to bear in mind that certain elements of the interior finishing were not taken into account. Because of the central role played by the auditoriums in the structure, the interior finishing is expected to be of the foremost quality, and we would expect proper finishing to be a time-intensive activity. As was the cost for the costs, the absence of certain interior finishing in the estimate thus reflects only the fact that the design did not provide sufficient to estimate this component of the work rather than any lack of importance of this activity in the schedule.

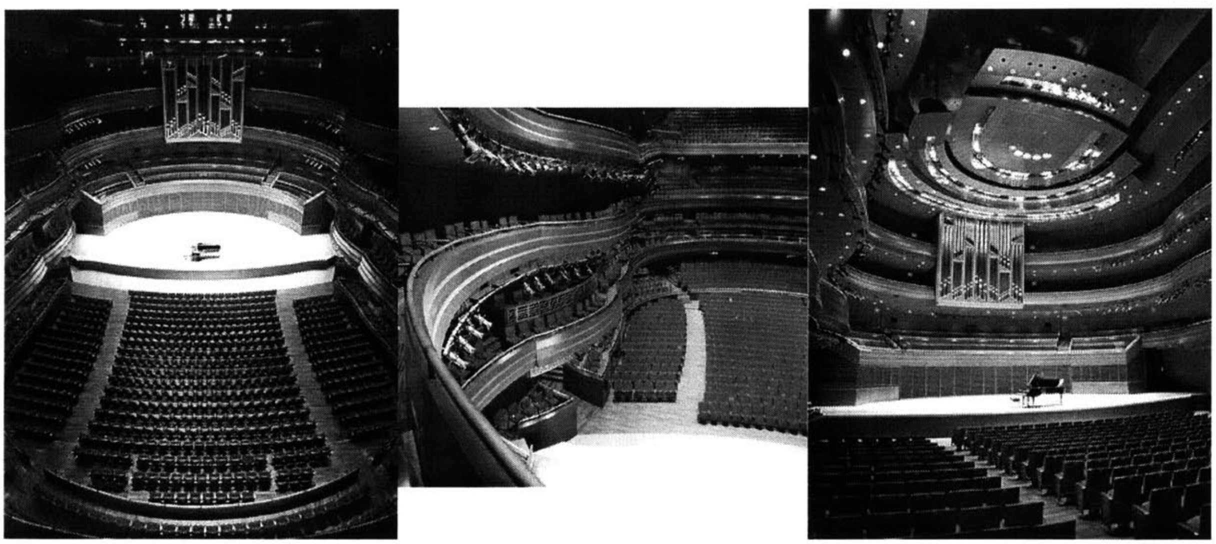


Figure 20: Kimmel Center for the Performing Arts

An auditorium is a highly intricate structure. More than being able to host an important crowd of spectators, it requires an elaborate sound system and is carefully decorated.

Using RS Means data allowed me to estimate the amount of time to install the major pieces of typical of an auditoriums, such as seats, basic stage components, electrical and control items and fireproofing. Most of the descriptions of these items were relatively opaque, lacking details on what they included. This limited the reasoning about how the costs and time would have to be scaled for the concert hall. As was noted for the cost estimate, a rough count has been attributed to each of them so as to be able to take them into account. Hence, the estimation is not completely accurate, but gives a good lower bound estimate of the construction length. When the activities seemed to be much too long, I used a high number of crews to stay in the 8 months period imparted for the interior finishing activity.

Following are some elements that can also counterbalance the lack of accuracy in the estimate:

- In contrast to many theaters, the 1,500 people venue will not have balconies, which will save an important amount of time. It is a simple flat auditorium, and it is than expected to be easier to furnish than elaborate theaters.

- The inclusion of two performance halls within the structure will allow crews to work in parallel. Assuming a construction start date of December 29, 2003, the structure will be done by the end of December 2004 and will allow the workers to start the interior finishing by the beginning of the year 2005. Because the concert halls are one on top of one another, coordination can be planned between the different crews (electrical, mechanical and so on) in order for them to efficiently perform cable-pulling, duct routing and other roughing-in in parallel.

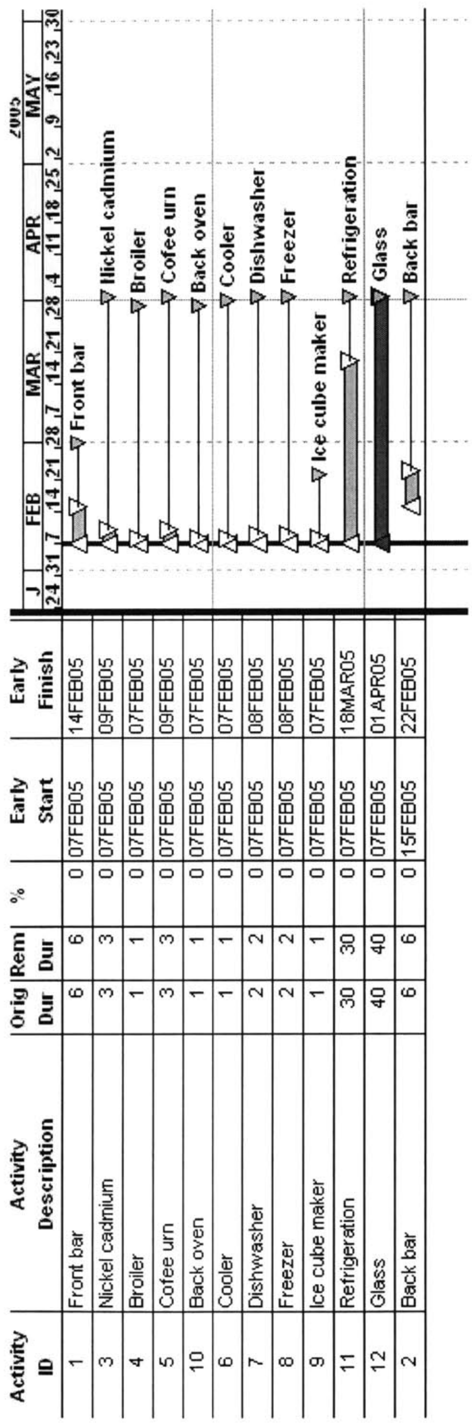
4.2.2 Restaurant detailed estimate

An estimation of the restaurant construction length was estimated in the same fashion used for the auditorium. Following is the table summarizing the information needed to calculate the total number of crew days for each activity:

Description	Crew	Daily output	Labor-hours	Unit	Building data	Total labor-hours	Total crew days
Bar							
Front bar	1 Carp	5.00	1.60	LF	30.00	48.00	6.00
Back bar	1 Carp	5.00	1.60	LF	30.00	48.00	6.00
Emergency lighting, 25 watt, battery operated							
Nickel cadmium	1 Elec	4.00	2.00	Each	10.00	20.00	2.50
Kitchen equipment							
Broiler	Q-1	8.00	2.00	Each	5.00	10.00	0.63
Coffee urn, twin 6 gallon	1 Plum	2.00	4.00	Each	5.00	20.00	2.50
Cooler, 6 ft, long	Q-1	6.00	2.67	Each	5.00	13.34	0.83
Dishwasher, 10-12 racks per hr	Q-1	3.20	5.00	Each	5.00	25.00	1.56
Food warmer, counter, 1.2 KW				Each	5.00		
Freezer, 44 C.F., reach-in	Q-1	4.00	4.00	Each	5.00	20.00	1.25
Ice cube maker, 50 lb. per day	Q-1	6.00	2.67	Each	5.00	13.34	0.83
Range with 1 oven	Q-1	8.00	2.00	Each	5.00	10.00	0.63
Refrigerators, Prefabricated, walk-in							
12'*20'	2 Carp	0.17	94.12	Each	5	470.59	29.41
Additional items							
Chairs and tables							
Chairs				Each	1500.00		
Tables				Each	1500.00		
Electronic							
PC				Each	5.00		
Software				Each	5.00		
Glass floor (restaurant)	2 Glaz	12.00	1.33	SF	12000.00	15960.00	1000.00
Total						16658.26	1052.14

Table 18: RS Means Restaurant Total Crew Days Estimation

With this table, Primavera was used to form a precedence diagram for the construction activities, and a restaurant schedule was derived (See Figure 21):



Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish
1	Front bar	6	6	0	07FEB05	14FEB05
3	Nickel cadmium	3	3	0	07FEB05	09FEB05
4	Broiler	1	1	0	07FEB05	07FEB05
5	Cofee urn	3	3	0	07FEB05	09FEB05
10	Back oven	1	1	0	07FEB05	07FEB05
6	Cooler	1	1	0	07FEB05	07FEB05
7	Dishwasher	2	2	0	07FEB05	08FEB05
8	Freezer	2	2	0	07FEB05	08FEB05
9	Ice cube maker	1	1	0	07FEB05	07FEB05
11	Refrigeration	30	30	0	07FEB05	18MAR05
12	Glass	40	40	0	07FEB05	01APR05
2	Back bar	6	6	0	15FEB05	22FEB05

Figure 21: Restaurant Interior Finishing Schedule

The schedule above suggests that the interior finishing restaurant can be done in two months.

5 CONCLUSION

The Boston Harbor Concert Hall presents an interesting case study for schedule and cost analysis for several reasons:

- It is structurally and architecturally elegant
- It is composed of different structural entities
- It houses two elaborate commercial type buildings

RS Means Square Foot Costs and RS Means Building Construction Cost Data are very helpful books to generate a first cost estimation, but their cost estimation applies much better to "simple" structures. When it comes to estimate the cost of structurally and architecturally elegant buildings as the Boston Concert Hall, composed of different structural entities and housing two elaborate commercial type buildings, RS Means data is limited. It can provide a lower bound of the cost but a detailed quantity take off will have to be done to give a much closer cost and schedule estimation.

Also, the cost of interior finishing shouldn't be underestimated in structures, especially when it houses buildings where very specific type of equipment has to be installed. This was seen here, where for the auditorium, the cost of the interior finishing is more than 40% of the total cost.

In terms of scheduling, RS Means documentation can give estimate of hour spent on an activity but other documents and experience is needed to create a schedule for a structure. The Boston Harbor Concert Hall had the advantage of having four separate entities that could almost be examined separately, but when it came to the schedule of the auditorium interior finishing, a great experience in electrical and mechanical engineering was required more than time estimation.

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