Mercy Health Muskegon

Mercy Campus Consolidation
Muskegon, MI

Abby Severyn | Structural Option | Honors
Adviser: Dr. Ryan Solnosky
April 1, 2019

Final Report

Mercy Health Muskegon

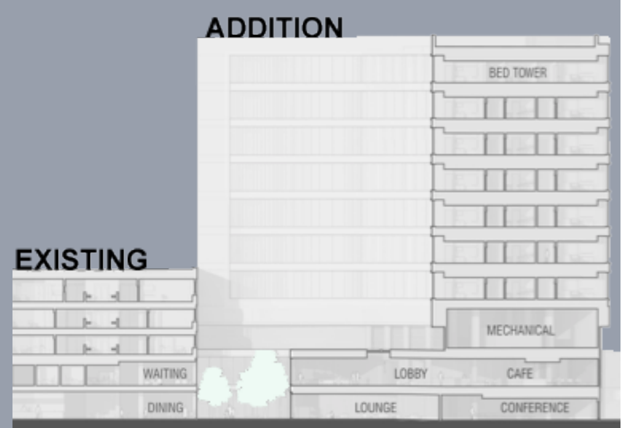
Muskegon, MI

Project Team

Mercy Health	Owner
The Christman Company	Construction Manager
HGA	Architect Landscape Architect Structural Engineer MEP Engineer
Fleis & VandenBrink	Civil Engineer
Materials Testing Consultants, Inc.	Geotechnical Engineer
Wiss, Janney, Elstner Associates, Inc.	Building Enclosure Consultant
Brigade Fire Protection	Fire Protection Consultant
Smith Seckman Reid, Inc.	Telecom Consultant

Building Info

- 10 stories, 167' Tall
- 380,925 Square Feet
- Patient-centered design
- Private patient rooms
- Courtyards and a healing garden provide green spaces
- Emergency and surgical specialties in the diagnostic and treatment departments
- Façade: metal panels, stone veneer, curtain walls



Original image, provided courtesy of HGA, has been modified.

Structural

- The steel-framed structure with composite decking supports gravity loads.
- The composite slab system acts as a diaphragm to transfer lateral loads to moment and braced frames.
- Spread footings are used in the shallow foundation system.

Construction

- Design-Bid-Build
- Construction Dates: Sept 2016 – Nov 2019
- Approximate Construction Cost: $186,000,000

Photo courtesy of HGA

Mechanical

- A variable air volume (VAV) system serves as the heating and cooling ventilation distribution system for the new addition.
- The addition includes a high efficiency hot water heating boiler plant and a chilled water-cooling plant.

Electrical

- 480Y/277V substations supply power to low voltage transformers for 208Y/120V distribution.
- An existing generator building houses four 1,000kW emergency generators.

Plumbing

- The new domestic water heating system is split into two systems to serve the high and low-pressure systems.

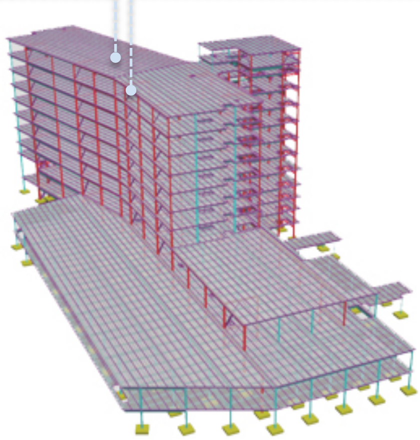
  A large portion of the plumbing scope is dedicated to the supply of medical gases.

EXECUTIVE SUMMARY

Located in Muskegon, MI, the Mercy Health Muskegon medical center is currently undergoing renovations and an expansion. This study encompasses a structural redesign of the 10-story addition with the objectives of cultivating a patient-centered healing environment, furthering sustainability efforts, and promoting system integration. An analysis of decision-making methods for the selection of structural systems in healthcare facilities is also included.

Existing Structure: Muskegon, MI

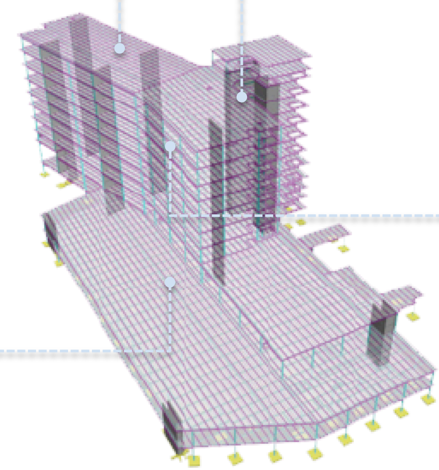
- Composite wide flange beams and girders
- W14 columns
- Steel braced frame (N-S) and steel moment frame (E-W) lateral system
- Shallow concrete spread footings



- Lower structural weight
- Fewer construction labor hours required

Redesigned Structure: Fort Lauderdale, FL

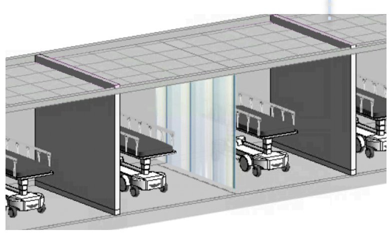
- Non-composite wide flange beams and girders
- W14 columns
- 8 ksi reinforced concrete shear wall lateral system
- Shallow concrete spread footings



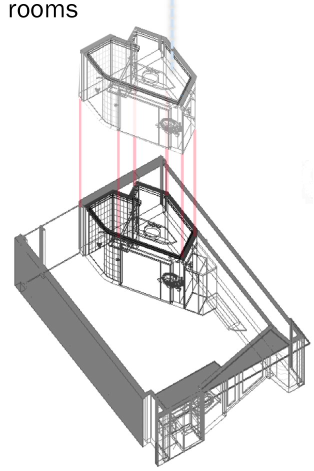
- $500,000 in cost savings
- Improved vibration performance in patient rooms and surgical rooms

Breadth Topics

- Improved acoustic performance and privacy in Post Anesthesia Care Unit bays by creating separate pods



- Construction time savings, increased safety, and waste reduction with the application of prefabricated patient bathrooms



Decision-Making Considerations

Methods used: Analytical Hierarchy Process (AHP), Choosing by Advantages (CBA), and Pugh Matrix (PM)

- General criteria: cost, sustainability (carbon emissions), future flexibility
- Architectural criteria: plenum depth, plenum coordination
- Construction criteria: repetitive members, enhancing/easing erection/construction time
- Structural criteria: system layout, structural member/system weight, minimizing structural depth

The results of the redesign indicate that a non-composite steel gravity system and reinforced concrete shear wall lateral system will result in better vibration performance, cost savings, and increased drift control for hurricane regions. The acoustic and prefabrication studies also recommend designs that further patient wellbeing and sustainability efforts.

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Acknowledgements

This undergraduate honors thesis was completed with much guidance and support from many people. I would like to acknowledge the following people for helping with this achievement:

- HGA Architects and Engineers, especially Chad O'Donnell and Jim Driscoll, for providing me with a thesis building and assisting me along the way.
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- Dr. Ryan Solnosky for his constant guidance throughout this project and willingness to dedicate his time whenever needed.
- Dr. Linda Hanagan for the years of honors advising and for extending to me your knowledge of vibration analysis.
- My friends who have been there for me more than ever this year.
- My family who always encourages me. Mom, Syd, and Jul, thanks for being my biggest supporters, best friends, and personal team of medical consultants.

1.0 Introduction

1.1 Purpose and Scope

This report displays the results for a study of the Mercy Campus Consolidation. This yearlong investigation includes an analysis of the existing structural design and a structural redesign of the gravity and lateral systems.

While the scope of the Mercy Campus Consolidation involves both renovations to existing facilities and new construction, the structural redesigns contained in this report will focus primarily on the new addition to the campus. While the existing structure meets all code strength and serviceability requirements, this investigation explores whether modifications to the structural system and architectural elements can further promote the following project goals:

- creating a patient-centered healing environment by improving vibration response and acoustic performance
- furthering sustainability efforts by reducing carbon emissions, using fewer structural members, and implementing a shorter construction schedule
- cultivating system integration by considering structural and mechanical plenum coordination, maintaining architectural integrity, and providing system flexibility

The structural redesign is based off a theoretical new location for the structure. Mercy Health Muskegon is part of Trinity Health, which has locations across the country. The proposed new location is Fort Lauderdale, FL, where Trinity Health currently has a 557-bed hospital. This new location is significant to the redesign as it places the structure in a hurricane region, which will greatly affect the lateral system.

The structural redesign also includes an alternative gravity system bay study, which provides the basis for the final structural system chosen for the redesign. The redesigned gravity system will be modeled with several different iterations and compared using three different multi-criteria decision-making methods. The results of these comparisons will also explore the application of formal decision-making methods in the structural design of healthcare facilities.

1.2 Mercy Campus Consolidation Overview

The Mercy Campus Consolidation consists of renovations to existing facilities alongside a new addition. The renovations involve changes to the existing five-story hospital facility, which consists of four stories and a full basement. The 10-story addition is to occupy a total of approximately 380,000 square feet and reach a height of 167 feet. Not including the penthouse mechanical spaces, the roof elevation is 147 feet. A diagram of the functional programs of the new building and its relation to the existing building can be seen in Figures 1 and 2. Construction on the project began in September 2016 and is expected to be complete in November 2019.

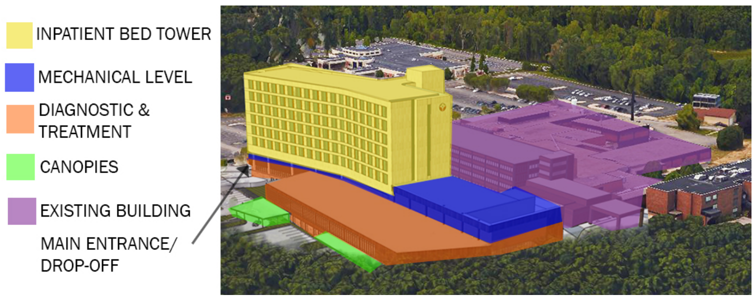


Figure 1: Mercy Health Muskegon Campus (original image provided by HGA)

Figure 2: Section of Existing Facility and Addition (original image provided by HGA)

The basement level, also referred to as the garden level, of the new building is partially exposed and is at the same elevation as the lowest level of the existing building. The garden level and a second story occupy a large footprint in order to incorporate multiple hospital departments and public areas. The two stories at the base contain emergency and surgical departments, also known as Diagnostic and Treatment (D&T). The public areas include a café, chapel, gift shop, healing garden, lobbies, lounges, and courtyards. Canopies make the entrances at these levels easily recognizable. A view of the main entrance on the west side of the new building is shown in Figure 3. As seen in the key plan (Figure 4), areas A, B, and C form the footprint of the new building.

Figure 3: View 1 - Main Entrance / Drop-off Area

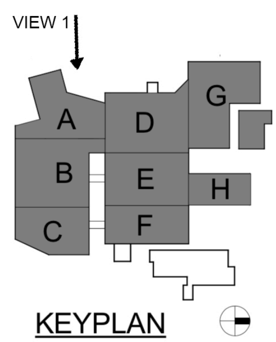


Figure 4: Key Plan (provided by HGA)

A mechanical level separates D&T and the seven-story inpatient bed tower, which occupies a smaller footprint. Single-occupancy patient rooms (Figures 5 and 6) line the perimeter along the long sides of the bed tower. The central spaces of the tower are dedicated to circulation and work areas for the medical staff. Figure 7 displays the architectural layout of a typical inpatient floor.

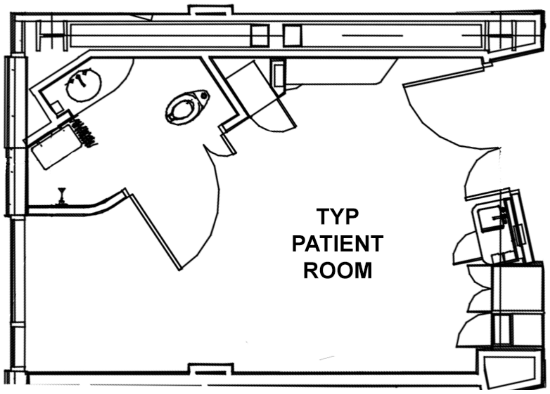


Figure 5: Typical Patient Room Plan
(provided by HGA)

Figure 6: Typical Patient Room

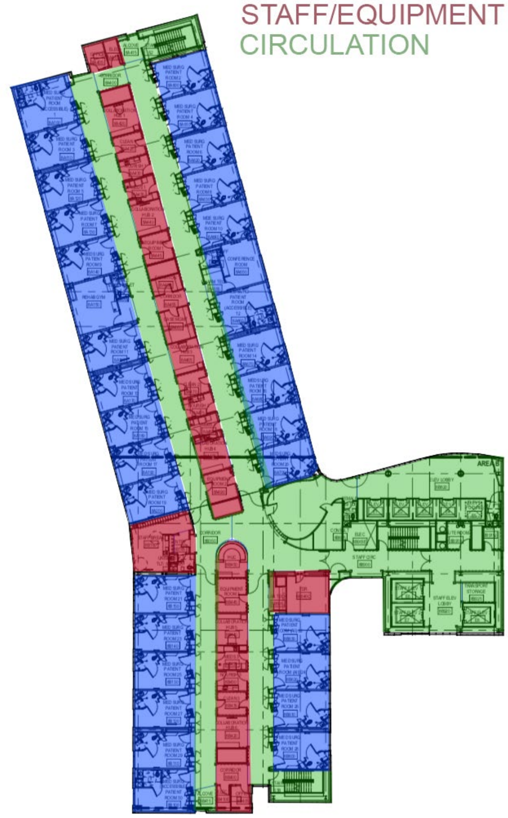


Figure 7: Typical Inpatient Floor
(original image provided by HGA)

The façade of the bed tower is mostly comprised of aluminum metal panels and aluminum curtain wall systems. The aluminum metal panels are mounted to insulated metal panels, which are attached to a stud back-up wall. The studs transfer lateral loads on the wall to the structure. Wall sections displaying the composition and attachment are shown in Figure 8.

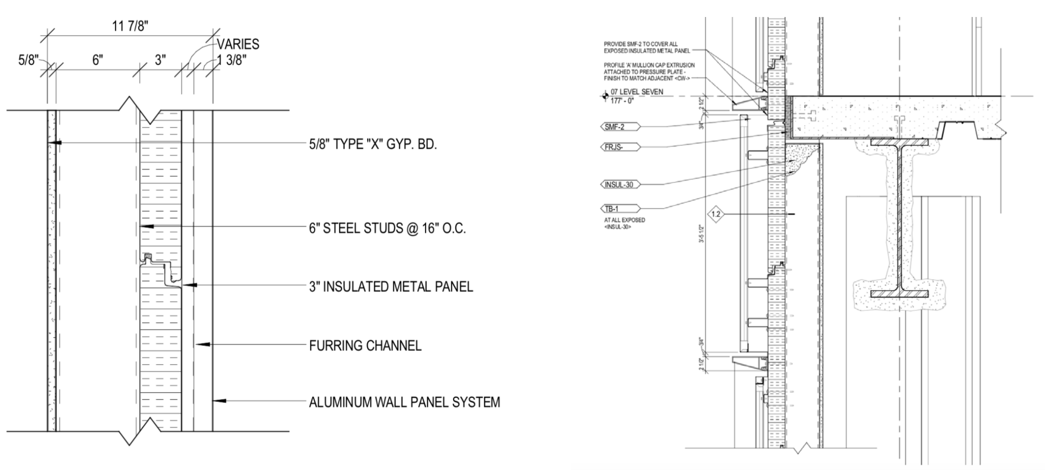


Figure 8: Exterior Metal Panel Wall Sections (provided by HGA)

The mechanical system is critical for the operation and daily use of the Mercy Health Muskegon medical center. The addition will be served by a variable air volume (VAV) system that is responsible for the heating and cooling ventilation distribution systems. The plumbing system is also important for fully sprinklered design requirements and medical gas supply throughout the hospital. Integration of the structural system with ductwork and piping of the mechanical system is a significant consideration for the structural redesign.

1.3 Structural Framing System Overview

Structurally, the addition is steel framed. A composite concrete slab and steel deck system transfers gravity loads to composite wide flange beams and girders that are supported by W14 columns. The columns then transfer vertical loads to shallow concrete spread footings. In the lateral system, the composite slab and deck system acts as a diaphragm to transfer loads to the lateral force-resisting elements. Steel moment frames with wide flange beams run along the east-west direction, and steel braced frames with wide flange beams and hollow structural section (HSS) braces resist loads in the north-south direction. W14 columns also support these frames and distribute loads to the shallow foundation system.

2.0 Loads and Codes

Discussed here are the load types that are applicable to the construction of the new Mercy Health Muskegon hospital building. Codes used for load calculations and structural designs are also detailed. The following codes will also be used for the gravity and lateral system redesigns.

2.1 Design Codes and Standards

The Mercy Health Muskegon addition is designed in accordance with the 2012 Michigan Building Code, which utilizes the 2012 International Building Code with Michigan amendments. Reference codes and standards, as referenced by the Michigan Building Code, and areas of use in the project design are as follows:

- ACI 318-05: concrete slabs, footings, and foundation walls
    - ACI 318-05 will also be used for shear wall analysis and design in the lateral system redesign
- ACI 530-05: masonry design and construction
- AISC 360-10: structural steel
- AISI: steel floor and roof decks
- ASCE 7-10: dead, live, snow, wind, and seismic loads; components and cladding wind loads; seismic restraint requirements for nonstructural (architectural, mechanical, and electrical) components
- AWS: structural welds for steel framing
- SDI: steel decking

2.2 Gravity Loads

Dead loads used for structural design include the weight of the structure (slabs, beams, columns, etc.) and all other permanent elements supported by or attached to the structure. Examples of these elements include walls, finish materials, and equipment. Since Mercy Health Muskegon is a hospital, large pieces of equipment such as surgical lights and anesthesia booms add a significant amount of dead load and must be given special consideration as additional support structures are needed. A summary of the dead loads used for the structural redesign are shown in Table 1.

Table 1: Dead Load Summary	
Typical Floor	104 psf
Single Ply Ballasted Roof of Concrete	111 psf
Single Ply Fully Adhered Roof on Concrete	103 psf
Metal Panel Wall	12 psf
Curtain Wall	15 psf
Typical Metal Panel and Curtain Wall Assembly	14.143 psf

Live loads are based on the occupancy or use of a space. Table 2 compares the design live loads, which will also be used in the structural redesign, to the code minimum required in ASCE Table 4-1. All design live loads are equal to the minimum code requirement. The design live load for mechanical and electrical rooms is not explicitly stated within the code because it accounts for the specific equipment contained within the area. In this project, the roof is not designed for public occupancy; therefore, the roof live load is included for loads during construction and maintenance.

Figures 9 and 10 show the design live loads used for typical D&T and bed tower floors. A typical D&T bay is designed to support an unreduced live load of 100 psf to meet the requirements for lobbies and first floor corridors. A typical bay in the bed tower is designed to support a live load of 80 psf, meeting the requirements for corridors above level one. These design values also meet the requirements for other floor locations that include a partition allowance, which allows for floor layout flexibility in the event of future modifications.

Table 2: Live Load Comparison				
Floor Location	**Live Load (PSF)**	**Reduced for Design**	**Partitions (PSF)**	**Code Minimum (PSF)**
Patient Rooms	40	YES	15	40
Offices	50	YES	15	50
Operating Rooms, Labs	60	YES	15	60
Library Reading Rooms	60	YES	15	60
Corridors Above Level One	80	YES	NA	80
Rehab Gymnasiums	100	YES	NA	100
Kitchens and Dining	100	YES	NA	100
Level One Retail	100	YES	NA	100
Lobbies and Level One Corridors	100	YES	NA	100
Stairs and Exits	100	NO	NA	100
Storage (Light)	125	NO	NA	125
Mechanical and Electrical Rooms	150	NO	NA	Note specified in code.
Ordinary Flat Roof	20	NO	NA	20

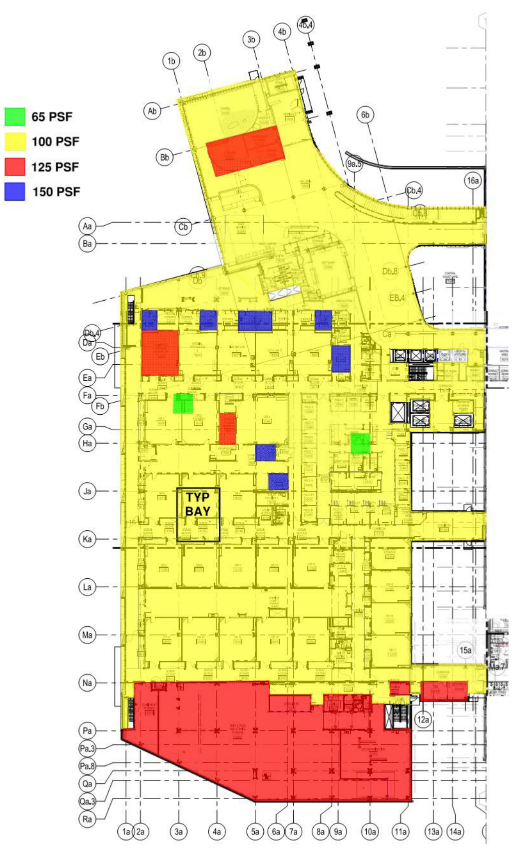


Figure 9: Design Live Loads for D&T Levels

Figure 10: Design Live Loads for Bed Tower Levels

For the existing structure, flat roof snow loads and drift loads are critical due to Mercy Health Muskegon being in Risk Category IV. A comparison of the flat roof snow loads used for analysis and design in the Muskegon location are shown in Table 3. With a change of location to Fort Lauderdale for the redesign, the snow loads will be removed from consideration and replaced with a 20 psf ordinary flat roof live load.

Table 3: Flat Roof Snow Load Comparison	
Design Snow Load	**ASCE 7-10 Code Minimum**
51 PSF	50.4 PSF

2.3 Lateral Loads

The source for determining wind loads for the main wind-force resisting system is ASCE 7-10 Chapter 27. The determination of these loads incorporates factors relative to Risk Category IV and Exposure Category B.

Table 4 shows values used for wind load calculations in the Muskegon and Fort Lauderdale locations. The gust factor, G_f, was manually calculated for the Muskegon location. Separate calculations were performed for the D&T (and mechanical)/bed tower levels, as indicated in the table, due to different footprints and exposure dimensions. As permitted by ASCE 7-10 26.9.1, G_f is taken as 0.85 for the Fort Lauderdale location. Aside from this, the only different is the wind speed, which is significantly higher for the Fort Lauderdale location as this is a hurricane region.

Table 4: Wind Load Inputs		
	Muskegon, MI	**Fort Lauderdale, FL**
Exposure Category	B	B
Wind Speed, V	120 mph	180 mph
Damping Ratio, β	0.01	0.01
K_d	0.85	0.85
K_{zt}	1.0	1.0
G_f (N-S, x-direction)	0.84/0.88	0.85
G_f (E-W. y-direction)	0.95/0.98	0.85

Seismic loads for the building structure are determined from ASCE 7-10 Chapter 12. Load determinations will utilize the seismic importance factor that applies to Risk Category IV. Table 5 shows values used for seismic load calculations in the Muskegon and Fort Lauderdale locations.

Table 5: Seismic Load Inputs		
	Muskegon, MI	**Fort Lauderdale, FL**
Risk Category	IV	IV
Importance	1.5	1.5
Site Class	D	D
R (x and y-directions)	3	3
C_t (x-direction)	0.020	0.020
C_t (y-direction)	0.028	0.028
S_s	0.066 g	0.045 g
S_1	0.042 g	0.022 g
T_L	12 sec	8 sec

3.0 Existing Structural Framing Systems

Here is a detailed description of the elements that compose the existing gravity and lateral systems for the Mercy Health Muskegon medical center.

3.1 Gravity System

3.1.1 Typical Bay

While the inpatient bed tower has floors that are all very similar, the first two floors of the new building are more irregular due to the many different functions that are contained within the large footprint. Therefore, it is difficult to define a typical bay for the emergency and surgical department levels that is representative of the entire framing system at the base levels. Due to this, there are two typical bays, one for the bed tower and one for D&T. Figures 11 and 12 depict the bed tower floor framing layout and typical bay.

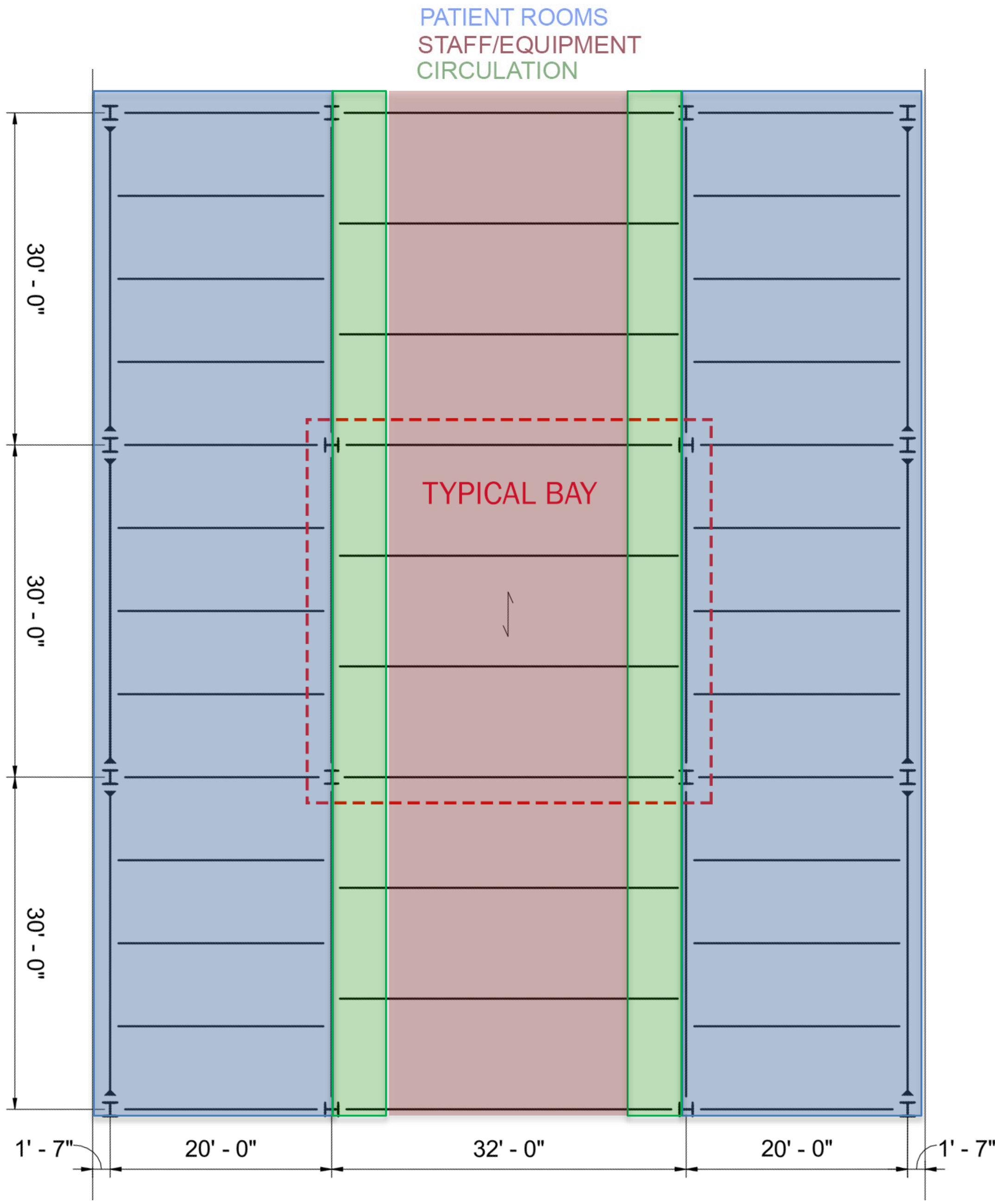


Figure 11: Typical Bed Tower Partial Floor Plan

There are two typical bays defined by the extents of the patient rooms. The 30' x 32' central bay is the larger of the two and is therefore chosen for the typical bay (Figure 12) at these floors. This typical bay is used for an analysis of the existing structure and alternative gravity system bay comparisons. The final gravity redesign utilizes this typical bay along with the adjacent 30'x20' typical patient room bay and a typical 24'x30'D&T surgical bay.

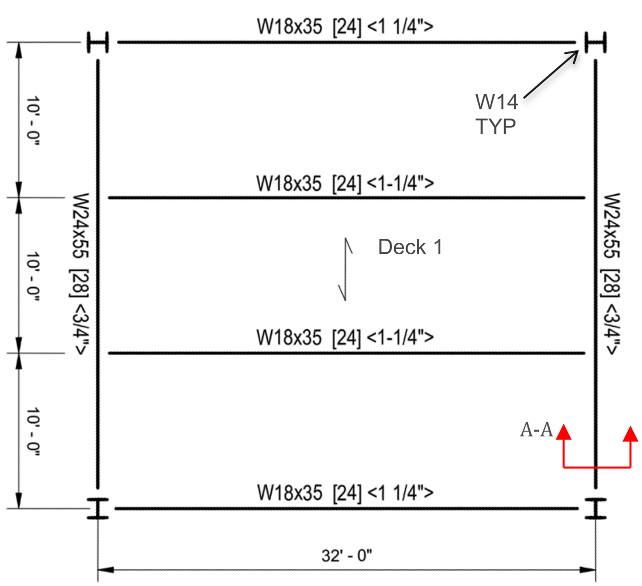


Figure 12: Typical Bed Tower Bay Framing Plan

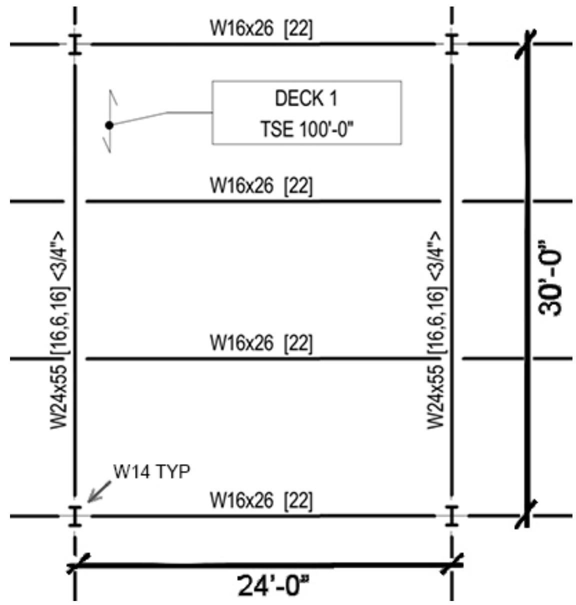


Figure 13: Typical D&T Bay Framing Plan (original image provided by HGA)

In the typical D&T bay (Figure 13), the layout is similar to the typical bed tower bay, but there are a few differences. The typical D&T bay is smaller at a size of 24'x30', and smaller section W16x26 beams spanning the short direction are not required to have camber. Beams maintain a 10' o.c. spacing but have only 22 evenly distributed studs along the 24' length. The 30' girders are again W24x55 and cambered ¾", but they have three sections of shear studs. There are sections of 16, 6, and 16 studs. The higher quantities of shear studs are located near the columns where the beam is more heavily loaded in shear.

An example of an irregular D&T bay is shown in Figure 14. This layout is different due to the additional framing required for medical equipment support in a procedure room.

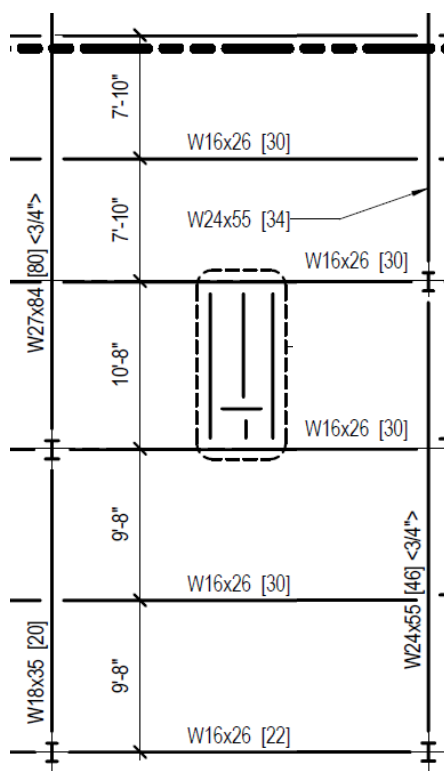


Figure 14: Example of Irregular D&T Bay (original image provided by HGA)

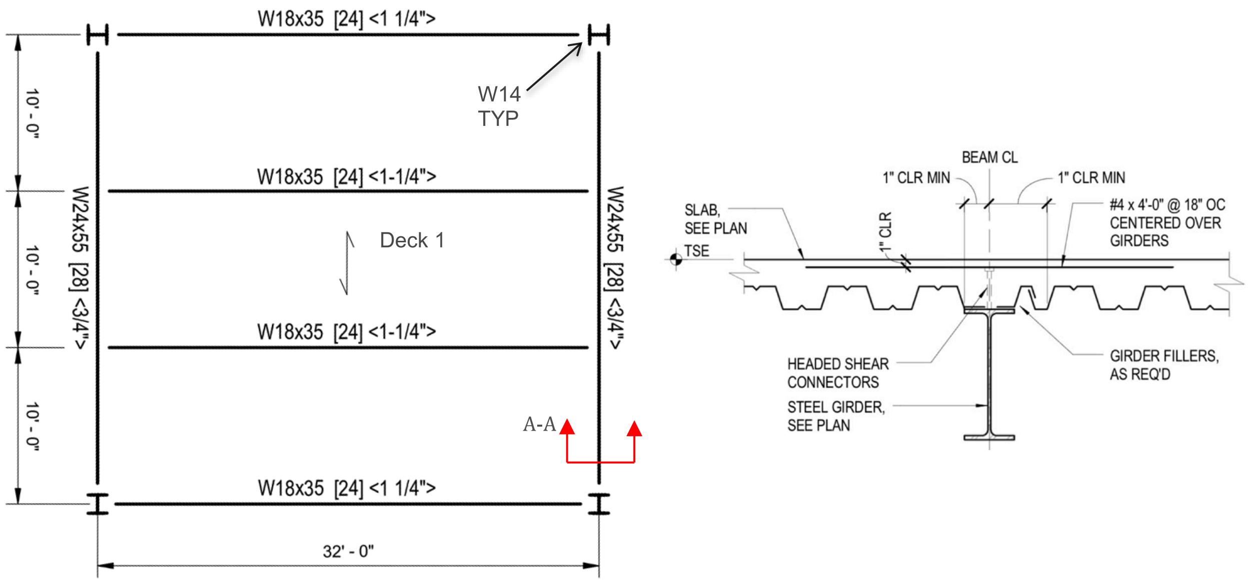


Figure 15: Typical Bed Tower Bay and Section A-A

At above grade levels, Deck 1 represents a typical composite floor system (Figure 15). It is constructed with an 18 gage, 3" composite galvanized steel deck and a 4½" normal weight concrete topping, reaching a total thickness of 7½". The deck is typically oriented perpendicular to the beams. Composite steel beams and girders are connected to the deck and slab with ¾" diameter and 5" long headed shear studs. In the typical bed tower bay, 24 studs along the W18x35 beams and 28 studs along the W24x55 girders are evenly distributed. Beams are spaced at 10' o.c. and span the long direction of the bay. With this 32' span, the beams are cambered 1 ¼" to avoid excessive deflection issues. The girders are cambered ¾".

Both typical bays contain wide flange columns with a nominal column size of 14". Columns range in size from W14x43 to W14x342. They are typically spliced every two floors using bolted or welded column splices.

3.2 Lateral System

The composite steel and concrete slab system acts as a diaphragm to transfer lateral loads to the lateral load resisting elements. The main lateral force resisting system consists of steel braced frames in the north-south direction and steel moment frames in the east-west direction. Figure 16 shows the locations of the moment frames (blue) and braced frames (red) that extend from the base through the entire height of the building. Both types of frames use wide flange beams and W14 columns. The braced frames are typically concentrically braced with HSS diagonal braces that range in size from HSS6x6x5/16 to HSS14x14x5/8. An elevation of a typical braced frame in the D&T area is shown in Figure 17. While this frame does not extend the full height of the building, the bracing layout is typical.

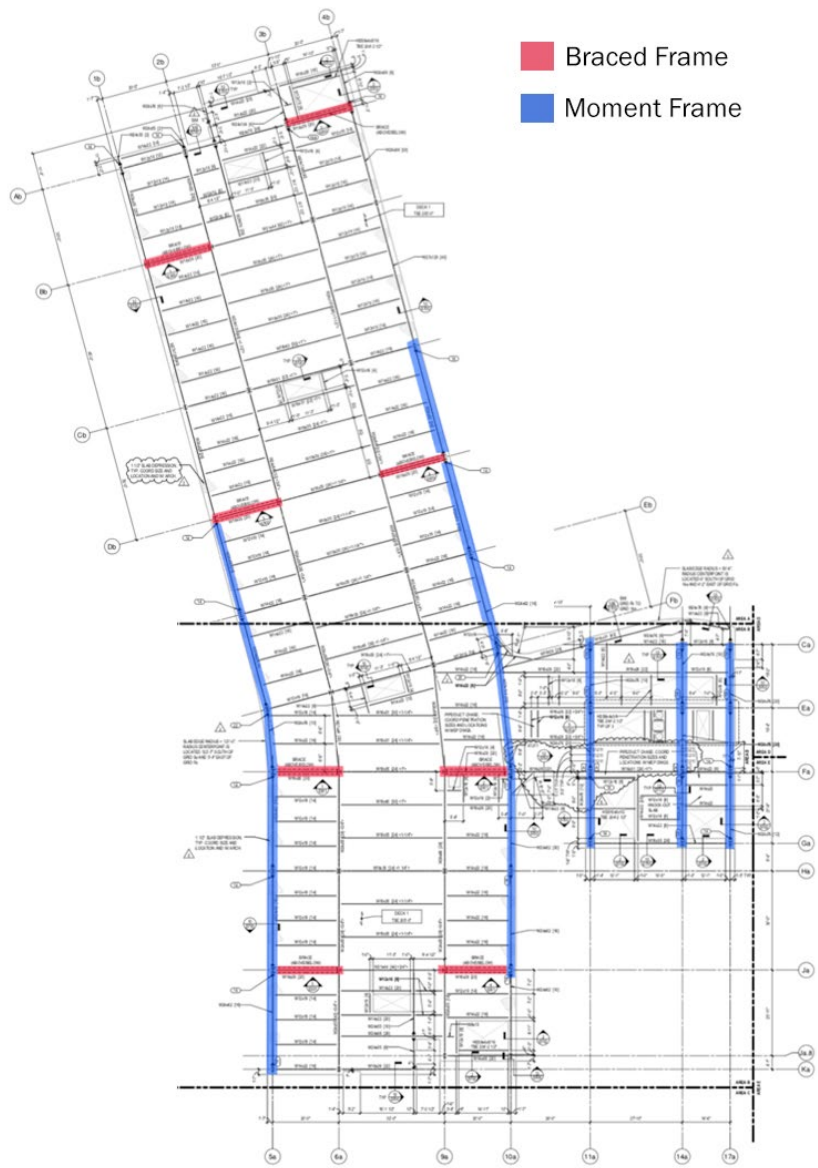


Figure 16: Lateral System Layout
(original image provided by HGA)

The braced frames and moment frames deliver lateral loads from the diaphragms to the foundation system and are typically supported directly by concrete spread footings. There is an exception at three steel moment frames that span between the central and viewing courtyards. In these instances, concrete moment frames at the garden level support the steel moment frames. A 3D view of the lateral system modeled in ETABS is shown in Figure 18.

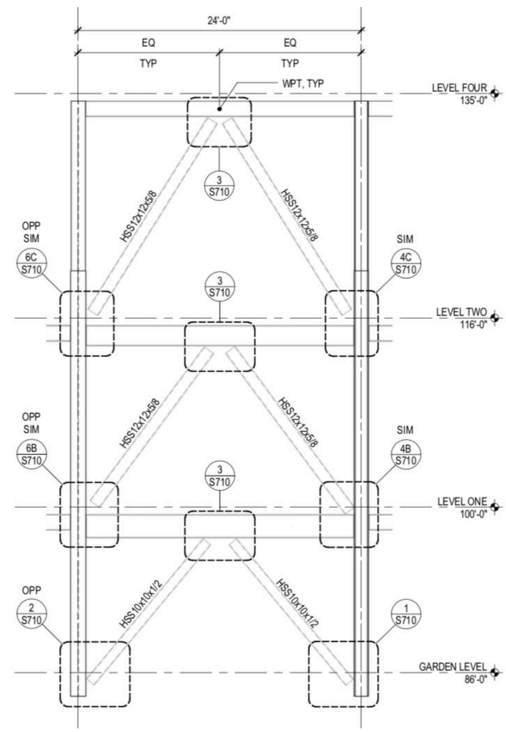


Figure 17: Typical Braced Frame Layout (provided by HGA)

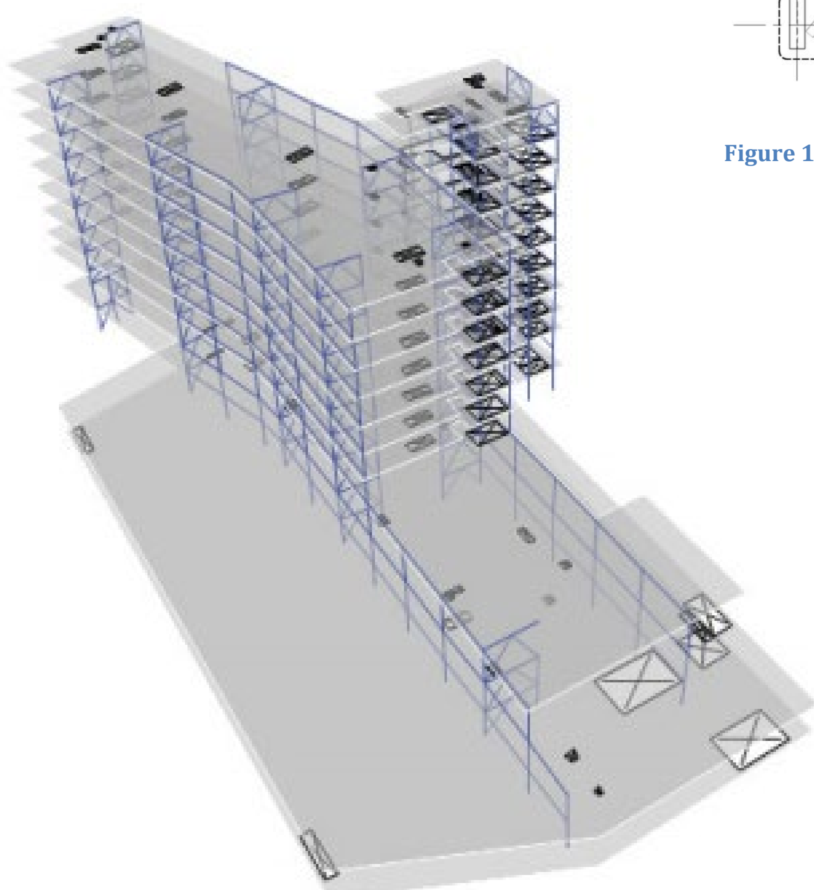


Figure 18: 3D View of Lateral System

4.0 Load Paths

Gravity loads on the structure follow a load path from the floor slab or roof deck to structural beams, followed by the girders and the columns. Finally, the columns transfer the vertical loads to the foundation system. A diagram of the load path for a gravity load applied at the roof is shown in Figure 19.

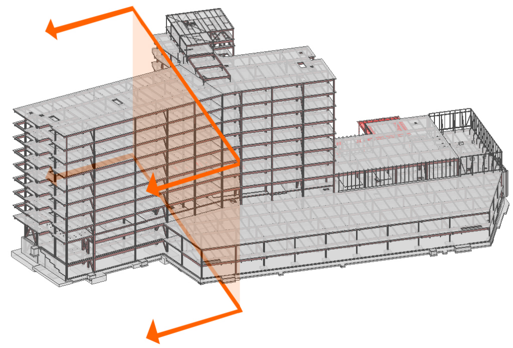


Figure 19A: Structure with Section Cut for Figure 21

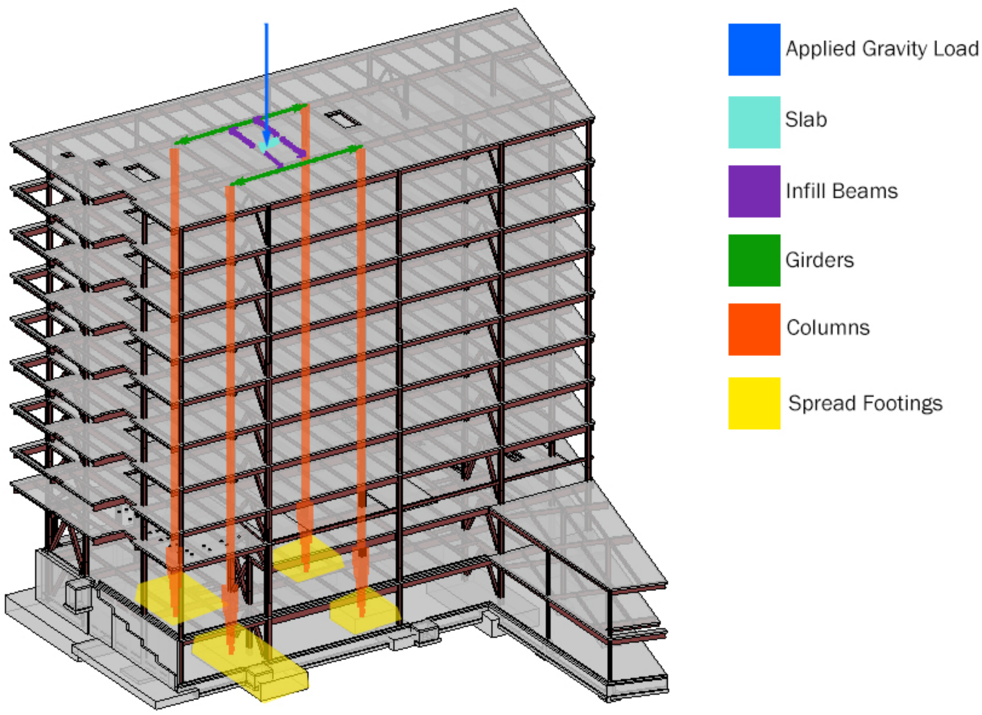


Figure 19: Gravity Load Path 3D Diagram

Lateral loads follow a different load path in which the composite steel and concrete slab system acts as a diaphragm to transfer loads. In the case of wind loads, the exterior wall is subjected to wind pressure and transfers the load to the slab. The slab then acts as a diaphragm and transfers the load to the lateral resisting elements, which then transfer loads to the foundations. When the slab is acting as a diaphragm, it acts similarly to a beam that is subjected to shear stress from the lateral loads and supported at the locations of the lateral frames. The slab also acts as a diaphragm to transfer seismic loads.

Figure 20 shows a sample lateral load path in the North-South direction where lateral loads are resisted primarily by braced frames. The load follows a path from the diaphragm to the beam and braces, then the columns, and spread footings.

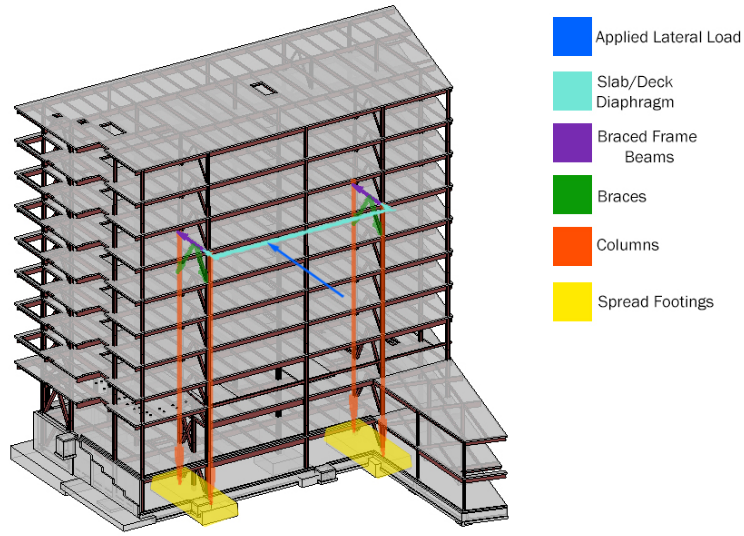


Figure 20: N-S Lateral Load Path 3D Diagram

5.0 Slab Depressions

Patient rooms in the bed tower contain a typical 1½" slab depression in bathroom showers to create a sloped floor so water is directed into the drain. This is a necessary consideration for vibration analyses (see upcoming Section 8.1) as the slab depression decreases the effective concrete thickness and lowers vibration performance. The slab depression location in a typical patient room is illustrated in Figures 21 – 23.

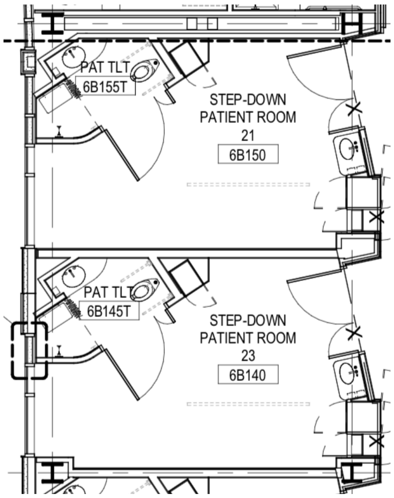


Figure 21: Typical Patient Rooms (provided by HGA)

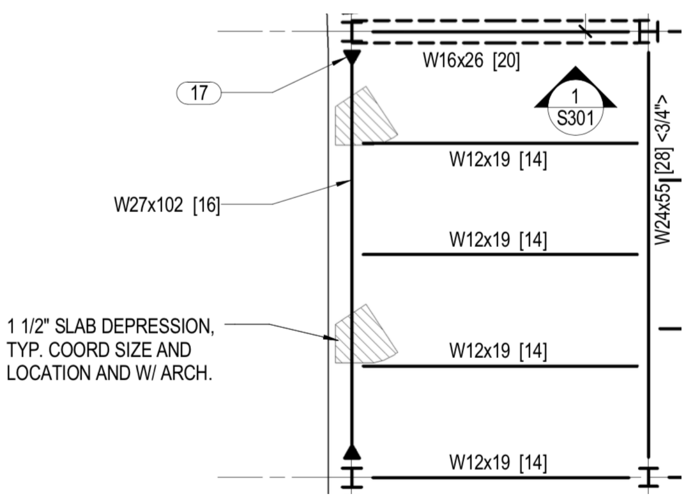


Figure 22: Typical Patient Room Framing (provided by HGA)

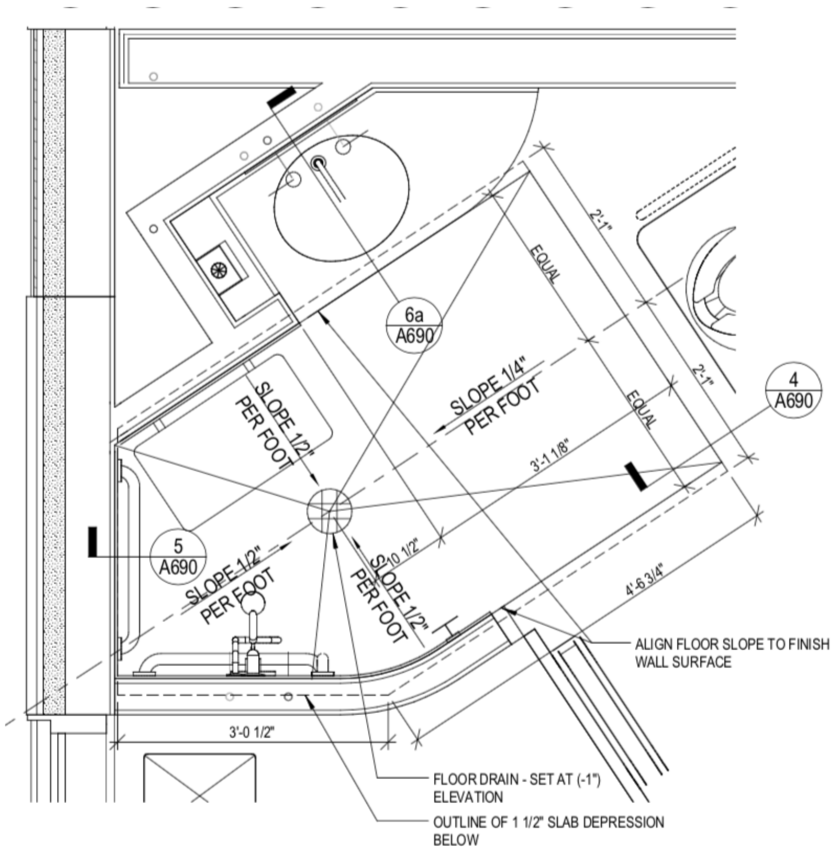


Figure 23: Slab Depression Diagram (provided by HGA)

6.0 Alternative Framing Systems for Gravity Loads

An alternative gravity system study was conducted to determine the best system for the gravity redesign. This investigation utilizes the 30'x32' typical bed tower bay. In addition to an analysis of the existing composite steel gravity system, the following systems were analyzed and considered for use in the redesign: (1) composite system with fewer infill beams, (2) flat slab with drop panels, and (3) one-way pan joists.

6.1 Composite System with Fewer Infill Beams

Figure 24 shows the preliminary design for the typical bay with a composite system that uses only one infill beam rather than two. The properties of Alternative System 1 are as follows:

- 3VLI16 composite deck
- 3 ½" lightweight concrete topping (6 ½" total slab thickness)
- f'c = 4000 psi
- 2-hour fire rating
- ¾" diameter, 5" long headed shear studs
- W14 columns

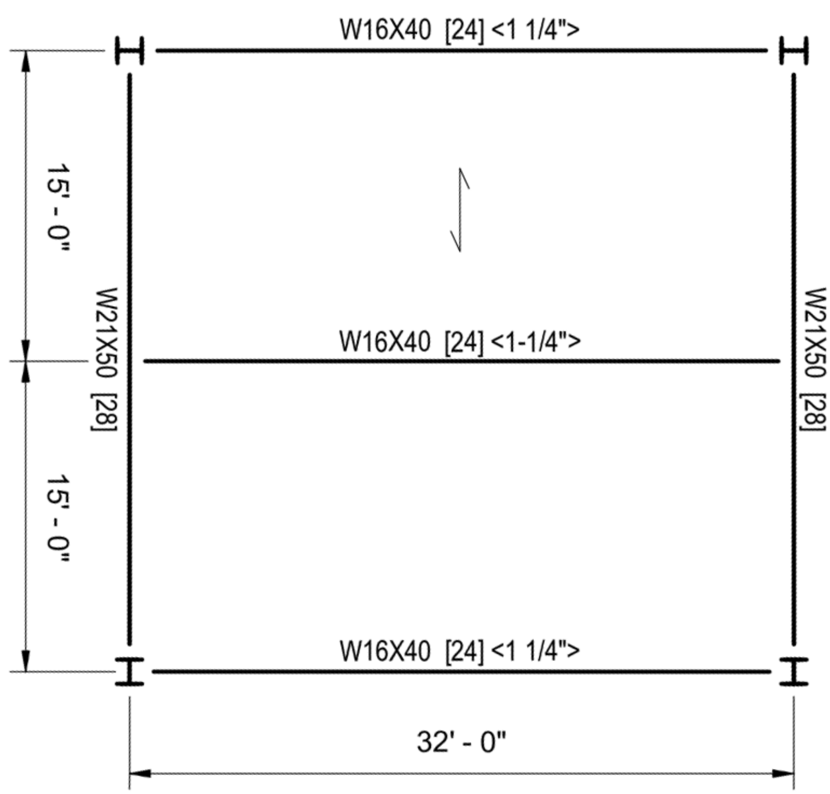


Figure 24: Alternative System 1 Typical Bay

6.2 Flat Slab with Drop Panels

Figure 25 shows the typical bay design with a flat slab and drop panels. A section across the entire floor is shown in Figure 26. Alternative System 2 characteristics are as follows:

- 12" thick concrete slab with 8" drop panels (20" total slab thickness)
- Normal weight concrete
- f'c = 4000 psi
- Reinforcing steel f_y = 60 ksi
- 20"x20" interior columns
- 17"x17" exterior columns

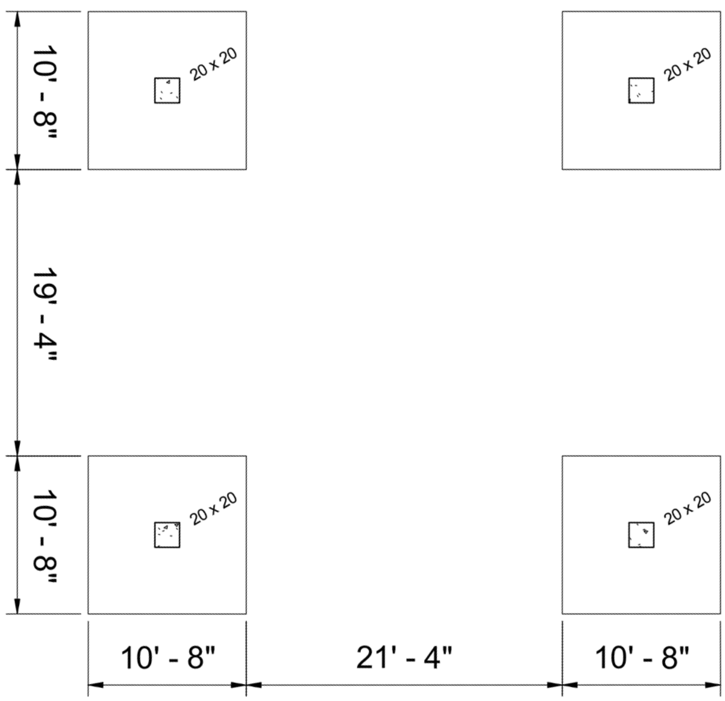


Figure 25: Alternative System 2 Typical Bay

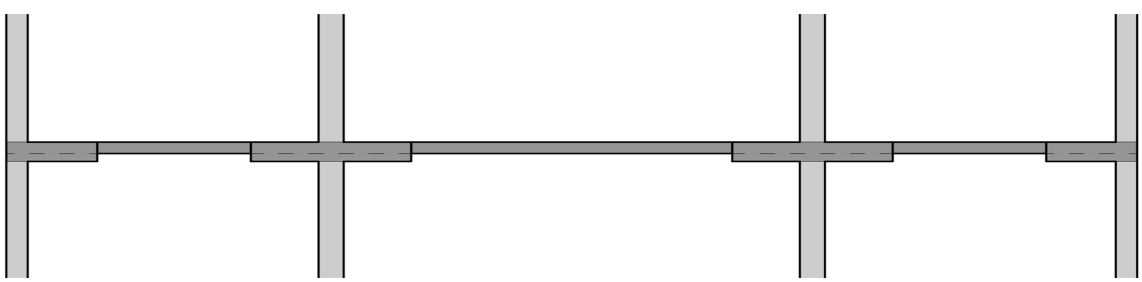


Figure 26: Alternative System 2 Floor Section

6.3 One-way Pan Joists

Alternative System 3 is a one-way system composed of concrete pan joists. A typical bay and floor section are shown in Figures 27 and 28. The system properties are as follows:

- 3” topping slab
    - Reinforcing: #4 at 7”
- 14” deep rib
    - Reinforcing: (2) #5 per rib
- 30” forms with 6” wide ribs
- 46”x14” concrete girders
- f’c = 4000 psi
- Reinforcing steel f_y = 60 ksi

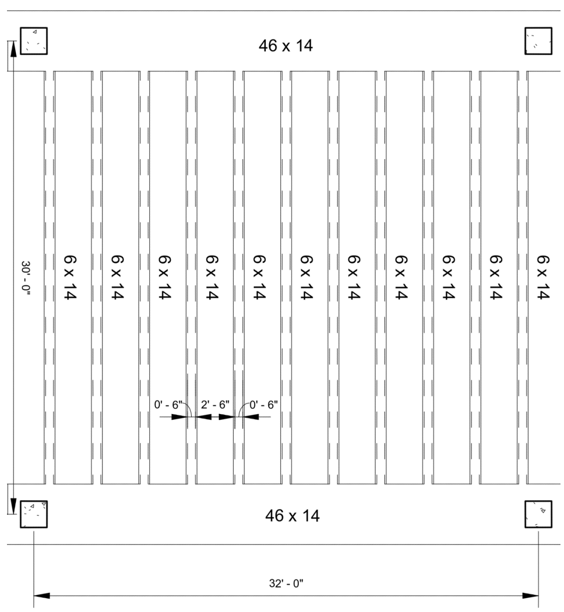


Figure 27: Alternative System 3 Typical Bay

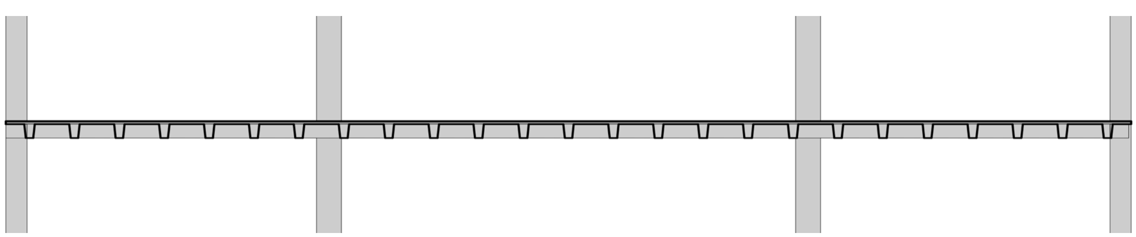


Figure 28: Alternative System 3 Floor Section

7.0 Framing Systems Summary Comparison and Recommendations

7.1 System Impacts and Considerations

For system comparisons, the impacts of the existing and alternative systems are considered in relation to public health, safety, and welfare; global, cultural, and social factors; and environmental, economic, and sustainability factors. Architectural, mechanical, and construction impacts are also considered.

7.2 Systems Summary and Decision-Matrix Comparison

The primary features of each system are summarized in Table 6. It is important to note that the cost estimates include only material costs. Based on these elements and considerations, a decision matrix (Figure 29) was used to determine which alternative should be further investigated.

Table 6: Systems Summary

	Existing System	Alternative System 1	Alternative System 2	Alternative System 3
Maximum System Depth	31”	27”	20”	17”
Weight (excluding columns)	81 psf	53 psf	161 psf	95 psf
Cost	$16.28/sf	$15.69/sf	$12.37/sf	$10.45
Notable Considerations	Requires fireproofing, possible vibration issues	- Requires fireproofing, possible vibration issues - Reduced number of members	Possible architectural/ mechanical conflicts, limited flexibility	Possible architectural/ mechanical conflicts, limited flexibility

The decision matrix uses weighted criteria. The most critical is integration since hospitals rely heavily on integration between engineering systems and architecture for efficiency. Cost is also important in healthcare projects, so higher weights have been given to this category, as well. The construction category involves ease of construction which accounts for any special considerations such as fireproofing, number of members, and framing/formwork complexity.

System Category	Specific Options Within System Category	Criteria							Total System Score	System Recommendation
		Cost		Construction	Integration					
		Weight of Framing	Cost Estimate	Ease of Construction	Architectural Integration	Structural Depth	Mechanical Integration	Design Flexibility		
Weight		3	3	1	2	3	4	2		
Structural System	Existing System	4	2	3	4	1	4	4	56	
	Alternative 1: Composite with 1 Infill	5	3	4	4	2	5	4	70	Y
	Alternative 2: Flat Slab with Drops	1	4	4	3	4	3	2	53	N
	Alternative 3: One-Way Pan Joists	3	5	3	2	5	2	2	58	M

Rating System	
5	Excellent
4	Good
3	Average
2	Fair
1	Poor

Recommended for Further Investigation	
Yes	Y
Maybe	M
No	N

Figure 29: Structural System Decision Matrix

After this investigation, the existing system is not recommended primarily due to its cost and structural depth. Based on the results of the decision matrix, the composite system with one infill beam will be further investigated.

A downside to this method of decision-making is that is highly subjective. Several of the criteria are vague and the weights are not determined by any formal method. Basing a decision on a simplified analysis such as this can have a significant outcome on the project if not done carefully and thoroughly. A further investigation of the decision-making process for the selection of structural systems for healthcare facilities will examine the application of several formal decision-making methods (see Section 13.7). The simplest of the decision-making methods in this investigation is known as the Pugh Matrix (PM), which was used to apply a formalized decision-making technique to this alternative gravity system bay comparison. This comparison uses a more accurate flat slab depth, (see Section 10.2), updated cost information, and detailed bay comparisons (Appendix A).

The PM analysis suggests that the composite system with one infill beam is the most favorable alternative, which agrees with the results from the informal decision-making process originally used. See Section 13.7.3 for the complete PM analysis. Since the composite steel system selection is verified, different steel system iterations will be considered for the gravity redesign.

8.0 Structural Depth Part 1: Gravity System Redesign

The gravity system redesign aims to promote a patient-centered healing environment, further sustainability efforts, and cultivate system integration. Based on the alternative gravity system bay comparisons, a steel gravity system will be used in the redesign. The selected system was composite steel, but the redesign also explores non-composite designs since they typically are more feasible for vibration control.

8.1 Vibration Analysis

The gravity system redesign begins with a vibration analysis. A primary goal of the redesign is to foster patient well-being. Large vibrations can have negative effects on hospital occupants, so developing a system with high-performing vibration responses is crucial. Vibrations must also be considered in areas with vibration-sensitive hospital equipment, such as operating and imaging rooms. The vibration analysis incorporates the following three types of areas within the Mercy Health Muskegon medical center: (1) a typical hospital patient room, (2) a typical interior (circulation/staff) bay, and (3) a typical surgical bay.

The hospital was modeled in RAM structural system in order to perform a vibration analysis using the RAM Steel Beam AISC Design Guide 11 vibration module. For this analysis, the three typical bays are all considered "perfect" bays since they are rectangle, have orthogonal framing, and have equally spaced beams. Perfect bays are more susceptible to perceptible vibration levels than irregular bays, so analyzing these three types of bays is sufficient for determining the most critical vibration responses in the bed tower and surgical areas.

Each of the three bays being analyzed has different vibration tolerance limits shown in Table7.

Table 7: Vibration Criteria Tolerance Limits	
Typical Hospital Patient Room Bay	6,000 mips
Typical Interior Bay	0.5% g
Typical First Floor Surgical Bay	4,000 mips

The typical interior bay is analyzed with the same criteria as an office. The circulation and staff areas have accessible travel routes, partitions, and several computers and pieces of medical equipment such as crash carts, but none that are vibration sensitive. Since the composition and functions of these two types of areas are similar, the vibration criteria were assumed to be the same.

On the first floor, the majority of the bays were designed based on the typical surgical bay vibration limits. As seen in Figure 30, the operating rooms and special procedure/lab rooms will be designed to meet a tolerance limit of 4,000 mips. The PACU bays are an exception. These areas are similar to patient rooms and are designed for a tolerance limit of 6,000 mips.

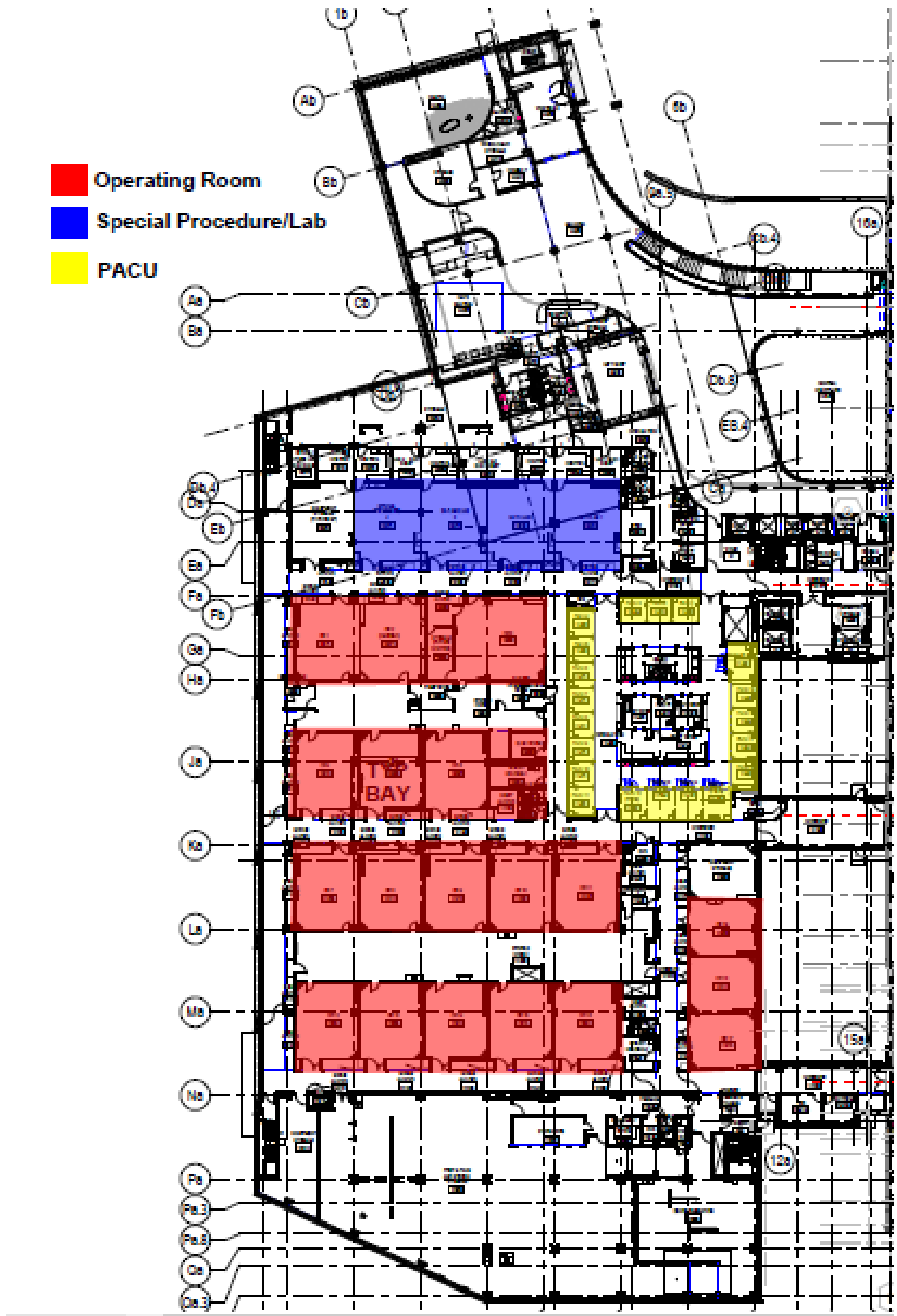


Figure 30: D&T Functional Area Diagram for Vibration Criteria

A special consideration for bed tower bays is the presence of slab depressions. There is a 1½" slab depression in each patient bathroom. The bed tower vibration analyses will use an effective slab thickness for all areas that is 2" less than the actual slab thickness. This is conservative but will allow for future design flexibility without compromising vibration performance.

The initial inputs for the 20'x30' typical hospital patient room bay are as follows:

- Criterion: Sensitive Equipment
- Equipment: User Defined
  - Velocity Limit: 6000 μ-in/sec

The initial inputs for the 32'x30' typical interior bay are as follows:

- Criterion: Walking
- Equipment: Electronic Office
  - Acceleration Limit: 0.50% of g
  - Damping Ratio: 0.05 (0.01 Structural System + 0.01 Ceiling and Ductwork + 0.03 Partitions/Fit-out)

The initial inputs for the 24'x30' first floor surgical bay are as follows:

- Criterion: Sensitive Equipment
- Equipment: User Defined
  - 4000 μ-in/sec

All initial loadings assume the typical 4 psf dead and 11 or 8 psf live loadings used for vibration analysis.

A preliminary vibration analysis performed using RAM is verified with hand calculations (Appendix A) in accordance with Design Guide 11 (DG11). Hand calculations were originally performed in reference to DG11 Second Edition, but the results were inconsistent with the RAM results. Further investigation led to the understanding that the RAM vibration module uses the DG11 First Edition analysis procedures. Therefore, the process follows the original DG11 but uses vibration limits from the second edition since they are more specific to each individual area.

The hand calculations and software analysis, performed for a preliminary non-composite design for the typical hospital patient room, had similar final results as shown in Table 8. They produced the same effective moment of inertia values but slightly different frequencies. This is due to differences in deck weight assumptions and equivalent uniform load calculations. RAM uses a conservative deck weight of 2 psf while the hand calculations used a weight of 3 psf. Additionally, RAM assumes beams in the adjacent bay are the same as those in the bay being analyzed. The hand calculations used the actual weights of the beams in the adjacent bay. Differences were also noticed between the total slab/deck weights, so the difference in deck weight will be accounted for as collateral loading. The final results had a maximum 6% difference. This is minimal and verifies the software vibration analysis results.

Table 8: Vibration Result Comparisons

Vibration Result Comparisons					
		DG11	**RAM**	**Evaluation V Limit (µin/sec)**	**% Difference**
Frequency (Hz)	Beam	13.13	13.23		
	Left Girder	13.68	13.77		
	Right Girder	7.78	7.88		
	Bay	6.69	6.77		
Walking Speed (steps/min)	100	31030	29539	6000	4.81
	75	6896	6564	6000	4.81
	50	1881	1764	6000	6.22

Criterion Not Satisfied

The desired vibration performance for the gravity redesign is to meet the evaluation limit for moderate (75 steps/min) and slow (50 steps/min) walking speeds or the 0.5% g limit for interior bays. The existing structure meets the 0.5% g walking vibration limit, but the redesign seeks to improve vibration performance by meeting more stringent criteria limits in order to maximize patient comfort and well-being as well as improve operating room safety.

8.2 Gravity System Iterations

The gravity system redesign will explore numerous layouts. These will be compared to each other with several decision-making methods to determine which is the best system for use in the redesign. The alternative systems are variations of composite and non-composite systems with different orientations and number of members.

The existing layout is composed of a slab/deck with a weight of 75 psf. To accommodate longer deck spans, the composite steel system with fewer infill beams that was analyzed in the preliminary alternative gravity bay study used a lightweight concrete slab weighing 48 psf. Since greater dead loads are beneficial to vibration performance, long span decks were investigated to increase the slab weight. Epicore 3.5 with a 7" total depth and weight of 62 psf was chosen for layouts with the original orientation but fewer members. Epicore 3.5A with a 6.5" total depth and 48 psf weight was chosen for rotated layouts to allow for a maximum deck span of 16'. (See Appendix A for Epicore technical information.)

The layouts that will be compared are shown in Figures 31-37. Each layout was designed to meet strength, serviceability, and vibration requirements. The structural weight, cost, carbon content, labor hours, number of pieces, number of different size pieces, number of studs (where applicable), average demand to capacity ratio, and vibration performance were determined for each bay. These results and comparison categories are then used to compare each design using the Analytical Hierarchy Process (AHP), Choosing by Advantages (CBA), and Pugh Matrix (PM) multi-criteria decision-making methods.

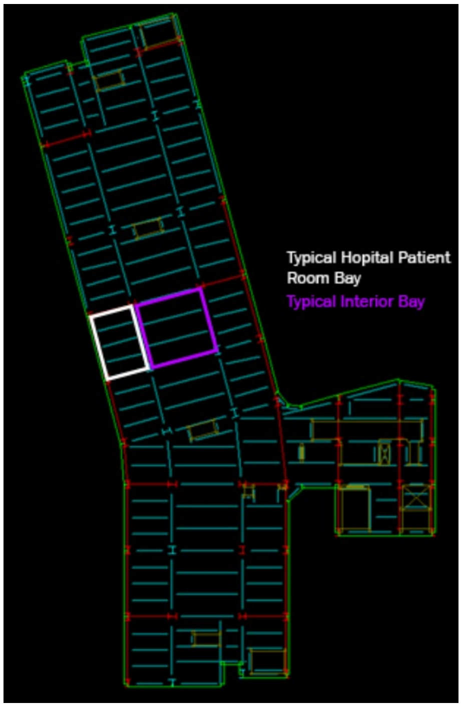


Figure 31: Original Bed Tower Layout

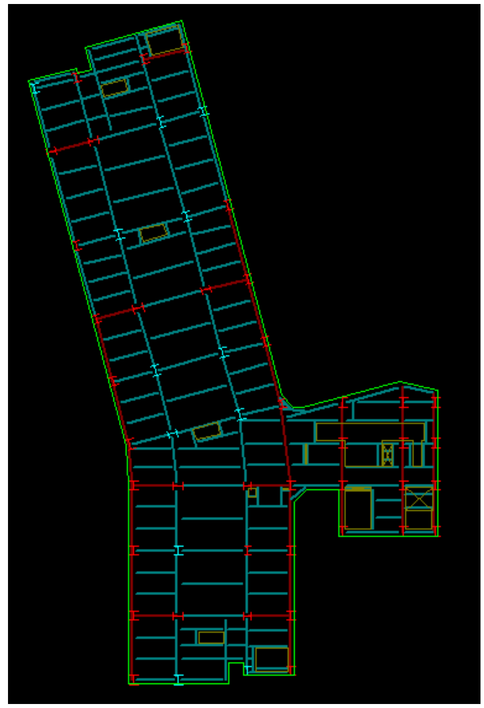


Figure 32: Bed Tower Layout with Fewer Infills

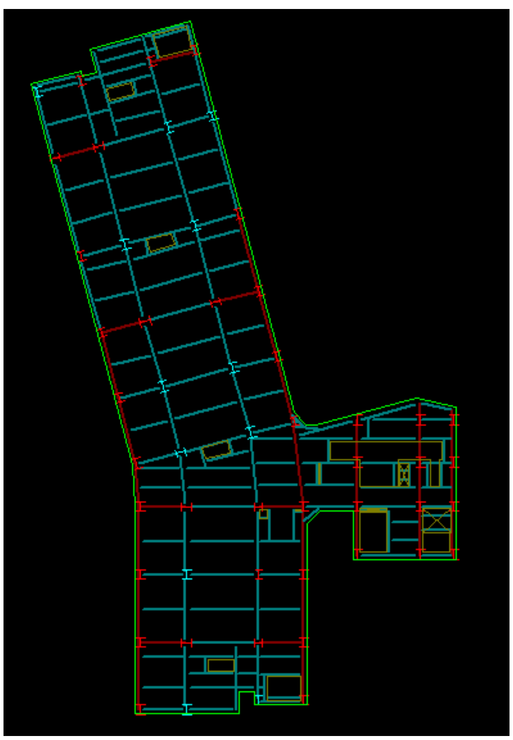


Figure 33: Bed Tower Layout with Fewer Infills and Modified Layout

Figure 34: Bed Tower Rotated Layout

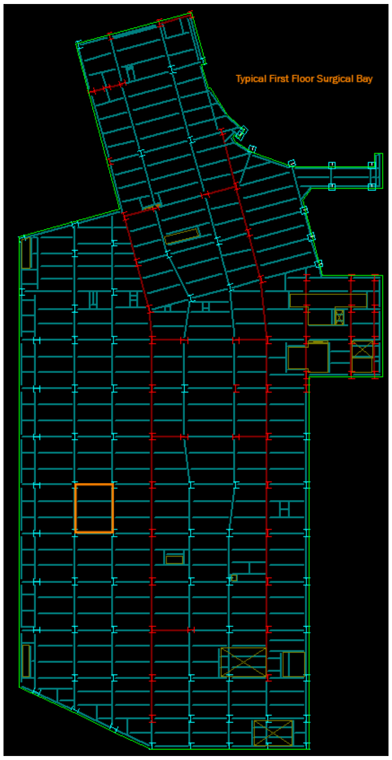


Figure 35: Original First Floor Layout

Figure 36: First Floor Layout with Fewer Infills

Figure 37: First Floor Rotated Layout

The bay comparisons are shown in Tables 9-11. Takeoff information is included in Appendix A. The original design did not meet the higher vibration performance requirements outlined in Section 8.1 and was therefore modified to meet these requirements. Overall, this system had the highest structural weight and total number of pieces. The lowest weight systems were those with the fewest number of pieces. These systems included both rotated layouts. In terms of sustainability, the non-composite system with the original layout had the lowest carbon emissions. This system also had the lowest material and labor costs for two of the three typical bays. Additionally, the larger quantity of members results in lower member depths, which is also true for the original composite design. The rotated layouts have the highest structural depth since they have fewer members that are spaced farther apart.

Table 9: Bay Designs and Vibration Comparisons

Bay Designs and Vibration Comparisons									
Model Number and Description	Bay Type	Member Sizes			Walking Speed (steps/min)			% g
		Beam	Left Girder	Right Girder	Slow, 50	Moderate, 75	Fast, 100	
1a -Original Composite Design	Typical Hospital Patient Room Bay	W12x19	W27x84	W24x55	2504	9316	41921	
	Typical Interior Bay	W18x35	W24x55	W24x55				0.288
	Typical First Floor Surgical Bay	W16x26	W24x55	W24x55	2015	7495	33728	
1b -Original Composite Design (Modified to Meet Vibration Requirements)	Typical Hospital Patient Room Bay	W14x26	W27x84	W24x76	1465	5451	24528	
	Typical Interior Bay	W18x35	W24x55	W24x55				0.288
	Typical First Floor Surgical Bay	W21x44	W24x68	W24x68	993	3695	16625	
2 - Composite with Fewer Infills	Typical Hospital Patient Room Bay	W18x35	W27x84	W24x62	1552	5773	25976	
	Typical Interior Bay	W18x35	W21x50	W21x50				0.421
	Typical First Floor Surgical Bay	W21x62	W24x84	W24x84	1021	3797	17085	
3 - Composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	W21x44	W27x84	W24x62	1566	5828	26224	
	Typical Interior Bay	W18x35	W21x50	W21x50				0.421
	Typical First Floor Surgical Bay	W21x62	W24x84	W24x84	1021	3797	17085	
4 - Composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	W21x50	W24x84	W24x84	1539	5727	25771	
	Typical Interior Bay	W16x31	W24x55	W24x55				0.423
	Typical First Floor Surgical Bay	W21x62	W27x84	W27x84	1057	3932	17694	
5 -Non-composite Design with Original Layout	Typical Hospital Patient Room Bay	W14x26	W27x84	W24x68	1557	5792	26063	
	Typical Interior Bay	W21x44	W24x68	W24x68				0.217
	Typical First Floor Surgical Bay	W18x35	W27x84	W27x84	1001	3722	16750	
6 - Non-composite with Fewer Infills	Typical Hospital Patient Room Bay	W18x35	W27x84	W24x68	1458	5423	24401	
	Typical Interior Bay	W24x55	W24x68	W24x68				0.241
	Typical First Floor Surgical Bay	W18x60	W27x84	W27x84	1063	3955	17797	
7 - Non-composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	W16x50	W27x84	W24x84	1546	5753	25888	
	Typical Interior Bay	W24x55	W24x68	W24x68				0.241
	Typical First Floor Surgical Bay	W18x60	W27x84	W27x84	1015	3778	16999	
8 - Non-composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	W21x50	W24x84	W24x84	1539	5727	25771	
	Typical Interior Bay	W21x50	W24x84	W24x84				0.254
	Typical First Floor Surgical Bay	W21x68	W24x84	W24x84	1050	3906	17578	

Table 10: Weight and Stud Comparisons

Weight and Stud Comparisons						
Model Number and Description	Bay Type	Bay SF	Number of Studs per Bay	Total Structural Weight of Bay (psf)	Floor Takeoff	
					Floor Weight (k)	Total Number of Studs
1a -Original Composite Design	Typical Hospital Patient Room Bay	640	98	86.02	152	2968
	Typical Interior Bay	960	152	84.69		
	Typical First Floor Surgical Bay	720	100	82.94	425	9816
1b -Original Composite Design (Modified to Meet Vibration Requirements)	Typical Hospital Patient Room Bay	640	116	88.38	158	3123
	Typical Interior Bay	960	148	84.65		
	Typical First Floor Surgical Bay	720	272	88.20	530	12772
2 - Composite with Fewer Infills	Typical Hospital Patient Room Bay	640	86	74.56	138	2368
	Typical Interior Bay	960	134	70.77		
	Typical First Floor Surgical Bay	720	204	75.60	415	9413
3 - Composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	640	74	74.13	131	2216
	Typical Interior Bay	960	134	70.77		
	Typical First Floor Surgical Bay	720	204	75.60	415	9413
4 - Composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	640	72	61.41	132	2224
	Typical Interior Bay	960	170	56.34		
	Typical First Floor Surgical Bay	720	166	61.17	420	9001
5 -Non-composite Design with Original Layout	Typical Hospital Patient Room Bay	640		86.19	177	
	Typical Interior Bay	960		85.12		
	Typical First Floor Surgical Bay	720		84.49	527	
6 - Non-composite with Fewer Infills	Typical Hospital Patient Room Bay	640		73.50	164	
	Typical Interior Bay	960		71.75		
	Typical First Floor Surgical Bay	720		72.60	510	
7 - Non-composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	640		74.56	167	
	Typical Interior Bay	960		72.75		
	Typical First Floor Surgical Bay	720		72.60	510	
8 - Non-composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	640		60.28	184	
	Typical Interior Bay	960		58.29		
	Typical First Floor Surgical Bay	720		59.47	523	

Table 11: Miscellaneous Bay Comparisons

Miscellaneous Bay Comparisons										
Model Number and Description	Bay Type	Carbon Content (kg CO_2)	Labour Hours	Structural Cost, Material Only ($/S.F.)	Structural Cost, Material and Labor ($/S.F.)	Number of Total Pieces (Beams and Girders)		Number of Different Size Pieces		Average Demand to Capacity Ratio
1a -Original Composite Design	Typical Hospital Patient Room Bay	12954.93	34.27	22.44	25.12	7	19	3	5	0.56
	Typical Interior Bay	17870.91	50.17	19.12	21.74	6		2		0.75
	Typical First Floor Surgical Bay	11866.18	34.12	16.79	19.13	6		2		0.7
1b -Original Composite Design (Modified to Meet Vibration Requirements)	Typical Hospital Patient Room Bay	14804.23	33.60	24.24	26.86	7	19	3	6	0.4
	Typical Interior Bay	17821.92	50.10	21.09	23.70	6		2		0.68
	Typical First Floor Surgical Bay	16500.44	38.56	21.21	23.90	6		2		0.4
2 - Composite with Fewer Infills	Typical Hospital Patient Room Bay	15722.22	34.03	23.70	26.37	6	16	3	5	0.4
	Typical Interior Bay	19125.43	47.51	18.03	20.49	5		2		0.89
	Typical First Floor Surgical Bay	18602.35	36.12	23.12	25.62	5		2		0.44
3 - Composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	15379.31	31.69	23.28	25.74	5	15	3	6	0.44
	Typical Interior Bay	19125.43	47.51	18.03	20.49	5		2		0.9
	Typical First Floor Surgical Bay	18602.35	36.12	23.12	25.62	5		2		0.44
4 - Composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	16958.35	32.69	25.22	27.76	5	15	2	6	0.35
	Typical Interior Bay	19485.50	45.72	16.85	18.95	5		2		0.99
	Typical First Floor Surgical Bay	18871.79	35.53	23.23	25.69	5		2		0.41
5 -Non-composite Design with Original Layout	Typical Hospital Patient Room Bay	13089.65	31.78	23.03	25.49	7	19	3	5	0.63
	Typical Interior Bay	18375.48	46.56	21.96	24.36	6		2		0.87
	Typical First Floor Surgical Bay	13228.05	34.34	21.02	23.38	6		2		0.84
6 - Non-composite with Fewer Infills	Typical Hospital Patient Room Bay	14889.43	32.57	24.03	26.56	6	16	3	5	0.52
	Typical Interior Bay	20276.65	43.87	21.44	23.69	5		2		0.84
	Typical First Floor Surgical Bay	15957.00	33.04	23.29	25.55	5		2		0.69
7 - Non-composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	15722.22	30.19	25.54	27.87	5	15	3	6	0.51
	Typical Interior Bay	21452.36	43.99	22.88	25.14	5		2		0.77
	Typical First Floor Surgical Bay	15957.00	33.04	23.29	25.55	5		2		0.69
8 - Non-composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	16076.57	31.47	25.14	27.58	5	15	2	3	0.31
	Typical Interior Bay	21770.78	44.13	22.18	24.45	5		2		0.83
	Typical First Floor Surgical Bay	17367.86	32.98	23.97	26.23	5		2		0.59

Not Applicable

Maximum Value for Bay Type

Minimum Value for Bay Type

Left girder for typical hospital patient rooms (in non-rotated layouts) indicates a perimeter girder.

Member sizes listed are the minimum sizes needed to meet vibration requirements for each bay.

All maximum and minimum values on this sheet do not include original composite design

Takeoffs for the typical interior bays are based off the controlling girder sizes for the neighboring patient room bays.

Before applying the formal decision-making methods, several alternatives were ruled out. Each system was ranked for structural weight, carbon emissions, and material cost. The best rank that could be obtained for each category was a 9 and the worst was a 1. The sum of the ranks was calculated for each individual bay and overall system. The two systems with the lowest total ranking were eliminated. As shown in Table 12, the eliminated systems were numbers 7 and 8.

Table 12: Gravity Bay Ranking

		Ranks					
Model Number and Description	Bay Type	Total Structural Weight of Bay	Carbon Emissions	Structural Cost, Material Only	Bay Sum	System Sum	
1a -Original Composite Design	Typical Hospital Patient Room Bay	3	9	9	21	58	
	Typical Interior Bay	2	8	6	16		
	Typical First Floor Surgical Bay	3	9	9	21		
1b -Original Composite Design (Modified to Meet Vibration Requirements)	Typical Hospital Patient Room Bay	1	7	4	12	42	
	Typical Interior Bay	3	9	5	17		
	Typical First Floor Surgical Bay	1	5	7	13		
2 - Composite with Fewer Infills	Typical Hospital Patient Room Bay	4	3	6	13	42	
	Typical Interior Bay	6	5	7	18		
	Typical First Floor Surgical Bay	4	2	5	11		
3 - Composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	6	5	7	18	47	
	Typical Interior Bay	6	5	7	18		
	Typical First Floor Surgical Bay	4	2	5	11		
4 - Composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	8	1	2	11	46	
	Typical Interior Bay	9	4	9	22		
	Typical First Floor Surgical Bay	8	1	4	13		
5 -Non-composite Design with Original Layout	Typical Hospital Patient Room Bay	2	8	8	18	47	
	Typical Interior Bay	1	7	3	11		
	Typical First Floor Surgical Bay	2	8	8	18		
6 - Non-composite with Fewer Infills	Typical Hospital Patient Room Bay	7	6	5	18	44	
	Typical Interior Bay	5	3	4	12		
	Typical First Floor Surgical Bay	6	6	2	14		
7 - Non-composite with Fewer Infills and Modified Layout	Typical Hospital Patient Room Bay	4	3	1	8	29	NOT CONSIDERED IN FUTURE COMPARISONS
	Typical Interior Bay	4	2	1	7		
	Typical First Floor Surgical Bay	6	6	2	14		
8 - Non-composite with Fewer Infills and Rotated Layout	Typical Hospital Patient Room Bay	9	2	3	14	39	NOT CONSIDERED IN FUTURE COMPARISONS
	Typical Interior Bay	8	1	2	11		
	Typical First Floor Surgical Bay	9	4	1	14		

The remaining systems were compared with AHP, CBA, and PM. More details about this procedure is found in Section 13.7. The results indicate that the non-composite design with the original layout is the best option. Consequently, this was the system used for the gravity redesign.

All members were modeled as non-composite and designed to meet strength, serviceability requirements. Typical beam and column spot checks are included in Appendix A. The spot checks display adequate strength and serviceability for the gravity members. Figures 38 to 41 show the existing structural design compared to the final redesigned typical bay member sizes. A cost estimate of the final gravity system is included in Section 10.1 along with an overall system comparison to the existing structure.

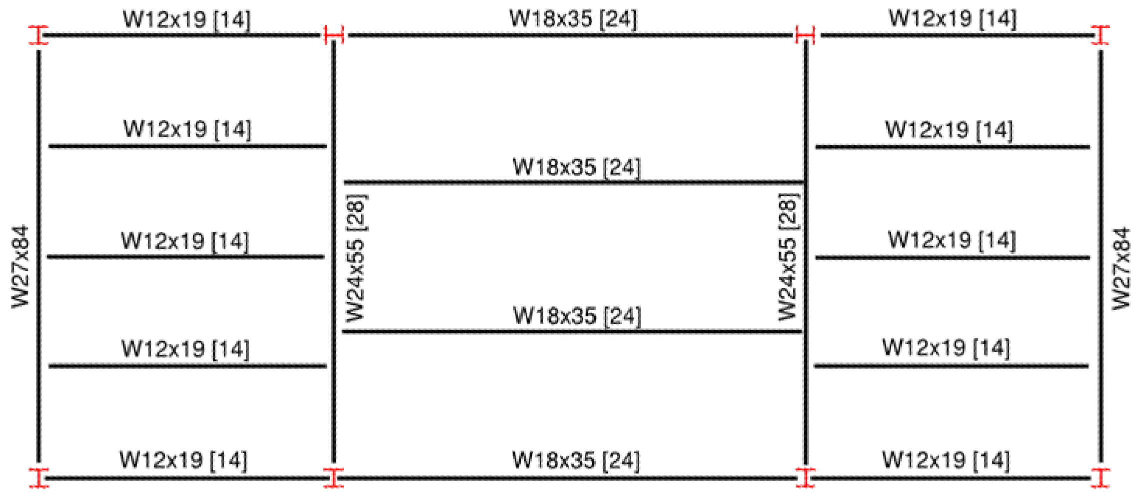


Figure 38: Existing Typical Bed Tower Bays

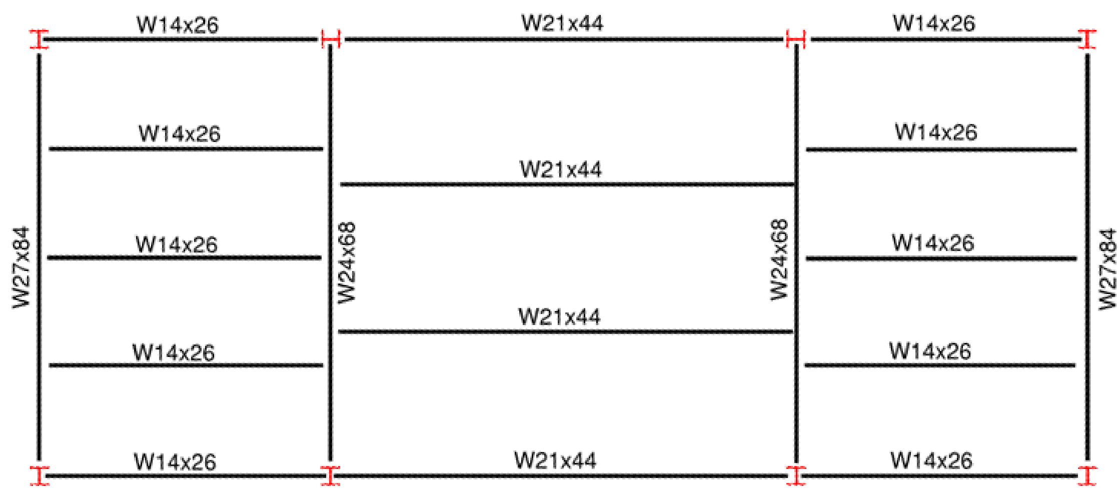


Figure 39: Redesigned Typical Bed Tower Bays

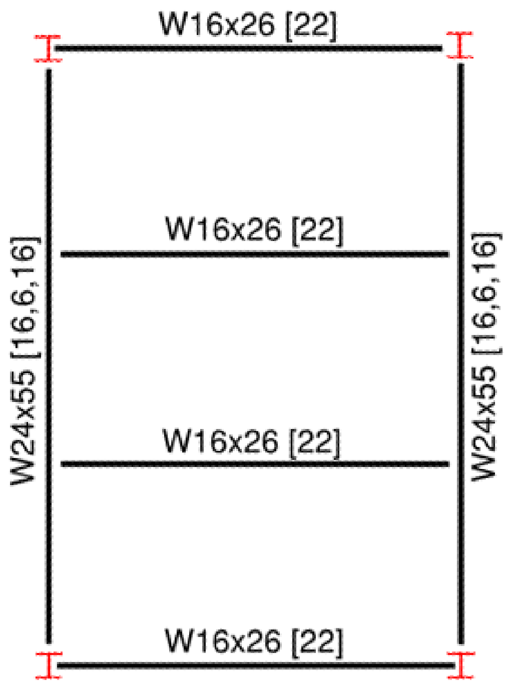


Figure 40: Existing Typical D&T Surgical Bay

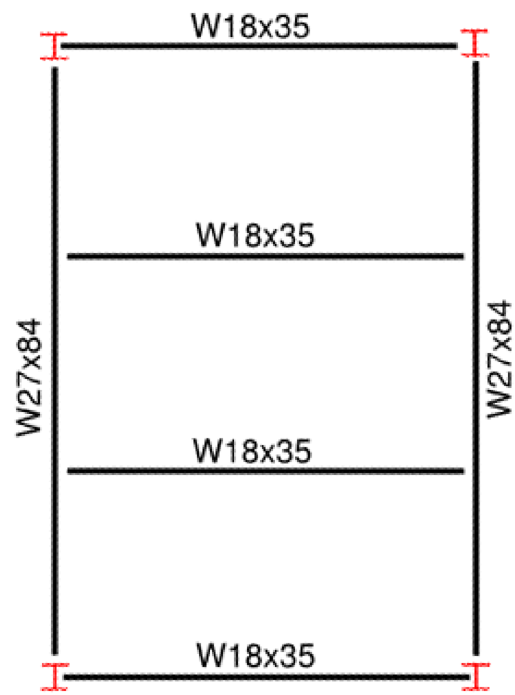


Figure 41: Redesigned Typical D&T Surgical Bay

9.0 Structural Depth Part 2: Lateral System Redesign

Mercy Health Muskegon is a member of Trinity Health, a health system with hospitals across the United States as shown in Figure 42. This study explores how the lateral system could be modified to meet strength and serviceability requirements if Trinity Health chose to use this design, or a similar design, in Fort Lauderdale, FL rather than Muskegon, MI. Trinity Health currently has a 557-bed hospital in Fort Lauderdale. Large healthcare networks are constantly updating and expanding their facilities, as seen with the Mercy Health Muskegon addition. Therefore, this redesign would be useful if the health system decided to add an addition or a separate healthcare facility to the Fort Lauderdale area.

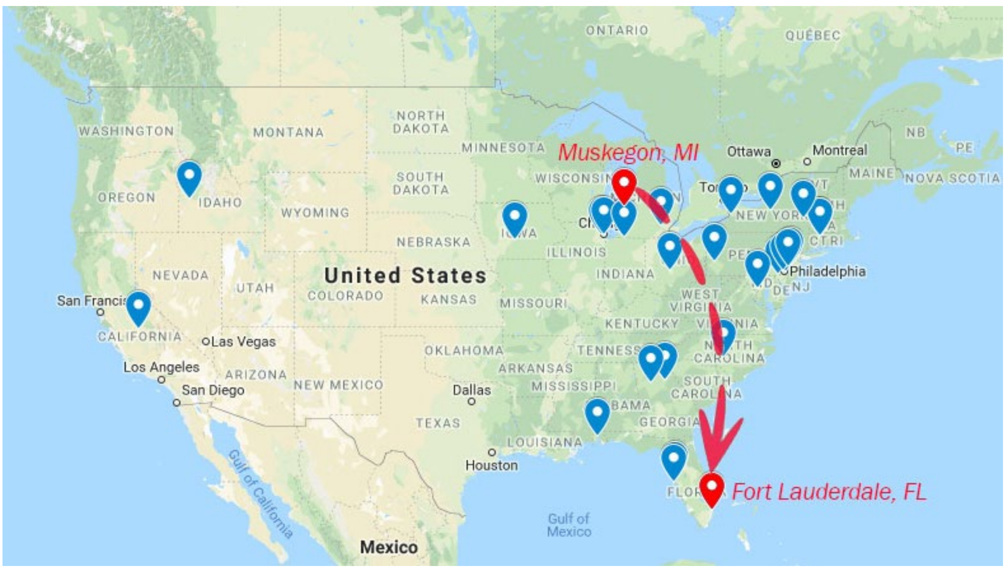


Figure 42: Trinity Health Locations (original image from www.trinity-health.org/hospitals-locations)

9.1 Lateral Load Comparisons

Table 13 displays a base shear comparison for wind and seismic loads, including manually calculated loads and automatically determined loads from ETABS and RAM Structural System. The design of the existing Mercy Health Muskegon structure is primarily seismic controlled, except for the controlling X-direction wind load. For the Fort Lauderdale location, the wind load base shears are significantly higher than the seismic base shears. This is to be expected since the structure is now in a hurricane region and SDC A rather than SDC C.

Consequently, the controlling wind loads will be considered for the lateral redesign. Table 14 and 15 show the applied story force wind load comparisons for manually calculated wind loads and automatically determined wind loads in ETABS and RAM Structural System.

Table 13: Base Shear Comparison						
	Original Design (Muskegon)			*Original Design (Fort Lauderdale)*		
Load Case	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**
Wind X	1744	1468	1734	3351	3771	4339
Wind Y	1043	883	1168	1776	1986	2656
Seismic X	1695	1697	1105	482	559	514
Seismic Y	1067	1067	742	482	559	593

Table 14: Wind Load Comparison X-Direction (North-South)						
	Original Design (Muskegon)			*Original Design (Fort Lauderdale)*		
Level	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**
Roof	113.09	107.82	139.14	244.57	778.96	473.18
Ten	170.11	160.82	170.77	363.17	158.03	455.51
Nine	166.81	142.28	167.55	355.96	156.37	128.75
Eight	165.0	161.68	164.05	352.04	382.48	493.37
Seven	159.77	139.9	160.18	340.61	319.26	378.41
Six	155.51	151.78	155.86	331.33	330.05	394.14
Five	150.22	155.87	150.06	319.79	339.07	405.08
Four	226.79	170.81	199.57	307.98	347.44	414.84
Three	40.74	37.81	51.83	74.69	354.95	423.71
Two	175.87	70.40	184.03	309.45	361.84	431.85
One	219.84	168.48	191.18	351.90	242.61	340.12
Σ	1743.77	1467.66	1734.22	3351.49	3771.05	4338.96

Table 15: Wind Load Comparison Y-Direction (East-West)						
	Original Design (Muskegon)			*Original Design (Fort Lauderdale)*		
Level	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**	**Manual Force (k)**	**ETABS Force (k)**	**RAM Force (k)**
Roof	72.86	66.23	92.12	138.75	149.23	241.13
Ten	111.17	98.92	118.19	200.35	222.57	315.11
Nine	108.91	97.04	115.71	195.94	218.33	307.77
Eight	107.69	94.98	113.02	193.54	213.71	299.68
Seven	104.12	92.72	110.05	186.54	208.56	290.77
Six	101.22	90.00	106.78	180.86	203.02	279.16
Five	91.61	89.27	102.59	173.79	200.29	236.19
Four	90.23	76.68	87.00	150.24	172.59	133.90
Three	51.71	60.52	49.37	77.53	126.95	196.44
Two	88.61	33.07	73.25	131.28	83.65	110.59
One	108.48	83.23	90.71	146.88	187.31	245.26
Σ	1036.61	882.75	1058.79	1775.70	1986.21	2656.00

The largest percent differences in the sum of the calculated loads for the Muskegon and Fort Lauderdale locations are 17% and 33% respectively. In each case, the automatically determined RAM Structural System loads result in the highest total applied load. Since the lateral system is being in RAM SS, this assumes the most conservative case.

9.2 Computer Modeling and Redesign of the Lateral System

The original lateral system, consisting of braced frames and moment frames, was modeled in RAM Structural System as shown in Figure 43. The original column and brace sizes were maintained, but some of the perimeter beams that are part of moment frames have been updated to meet the vibration performance goals. The auto-generated Fort Lauderdale wind loads were used to analyze the system. The resulting frame interactions are shown in Figure 44.

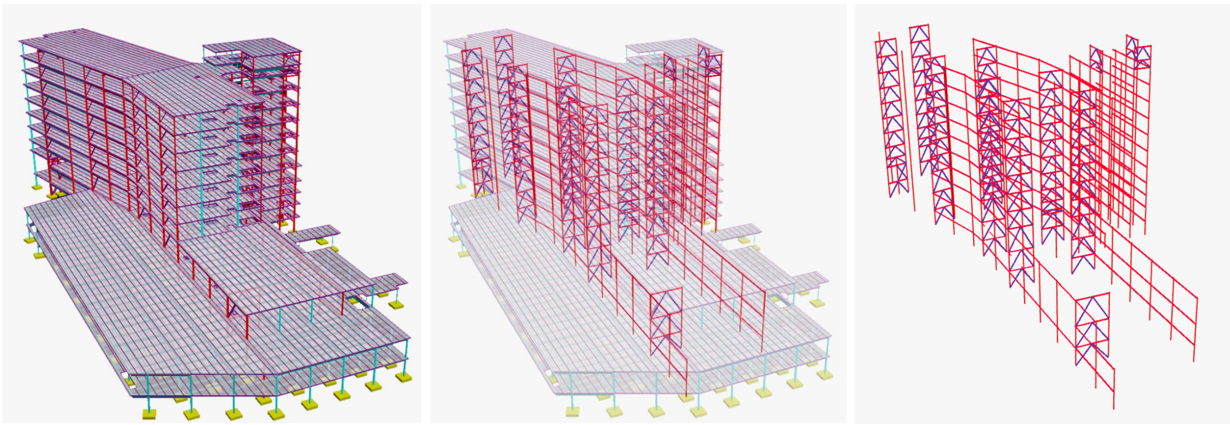


Figure 43: Existing Structural Systems Modeled in RAM SS

The members shown in red have an interaction greater than 1.0, indicating that they do not meet strength requirements. These members, and the members shown in orange and yellow with interactions ranging from 0.9 to 1.0, have been resized to meet strength requirements with an interaction less than 0.9. The interactions for this lateral system with upsized members is shown in Figure 45.

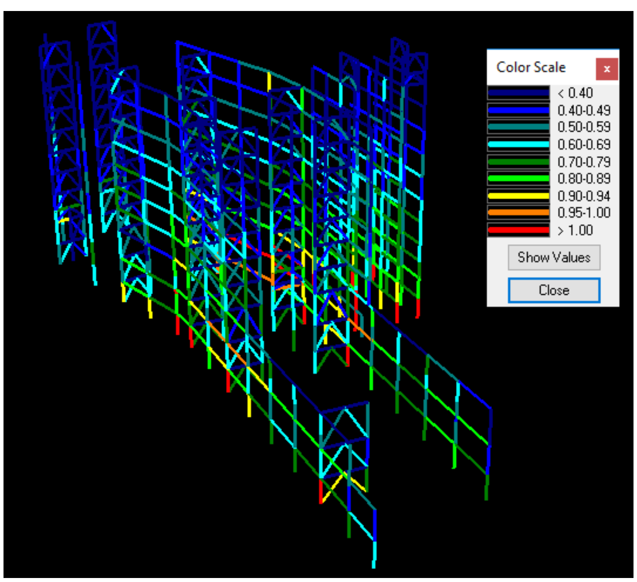


Figure 44: Existing Lateral System Interactions for Fort Lauderdale Location

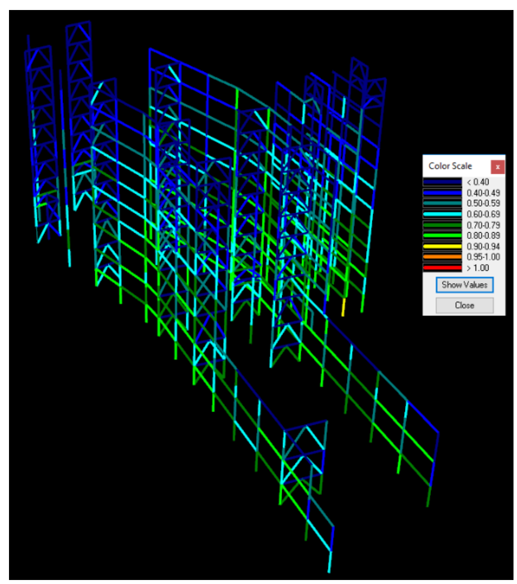


Figure 45: Updated Lateral System Interactions for Fort Lauderdale Location

The story drifts for the lateral model with the original member sizes are shown in Figure 46. Story drifts in the X and Y directions are plotted against an H/240 drift limit. Figure 47 shows the story drifts after changes were made to update members to meet strength requirements.

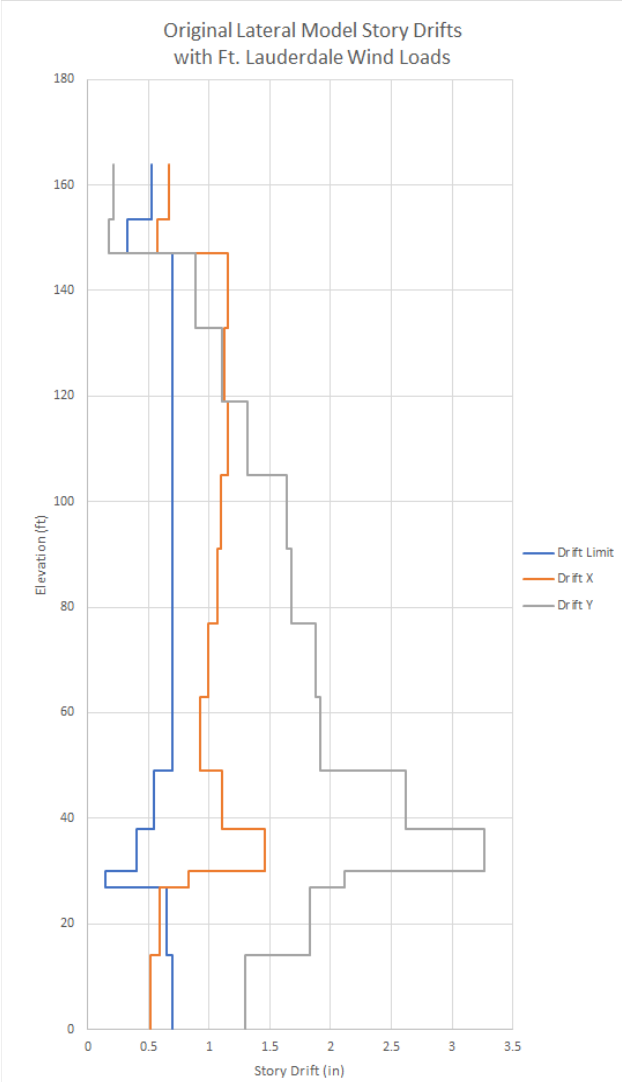


Figure 46: Original Lateral Model Story Drifts with Fort Lauderdale Wind Loads

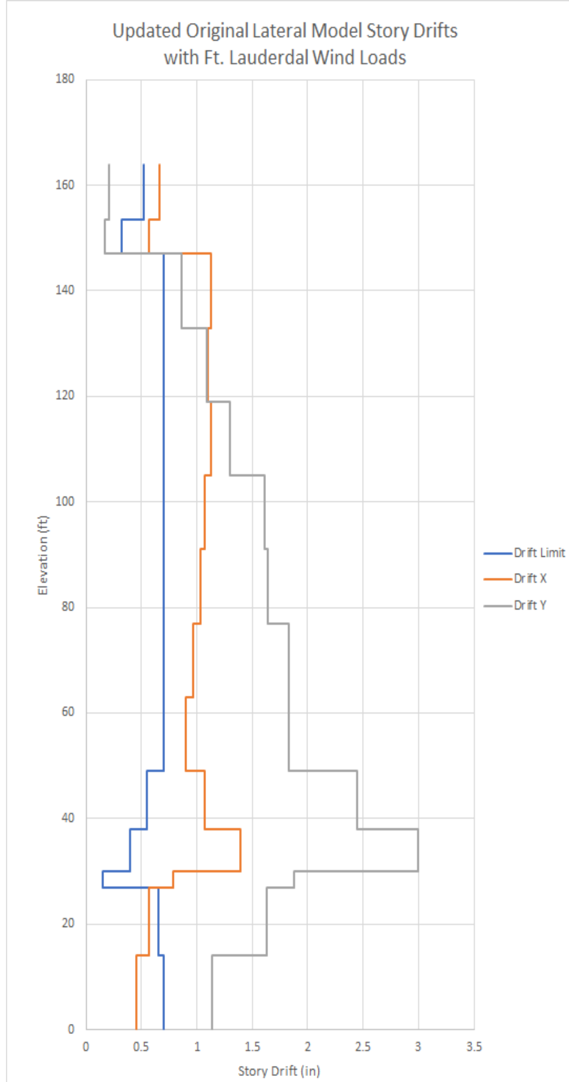


Figure 47: Updated Original Lateral Model Story Drifts with Fort Lauderdale Wind Loads

In both cases, the story drifts at almost every level in both directions exceeds the drift limit. Updating the original model to meet strength requirements causes the drifts to decrease slightly, but not enough to approach the drift limit. The maximum story drift is approximately 3", which is severe. Since all members meet strength requirements but still result in excessive story drifts, the design of the lateral system is controlled by drift. In order to meet the drift requirements using this same combination of braced frames and moment frames, the members would need to be upsized well beyond what is required for strength. Since this would not be the most economical or practical solution, a shear wall system is investigated to decrease drift.

The first step in this process was determining a preliminary shear wall layout to minimize the distance between the center of mass (COM) and center of rigidity (COM) in the X and Y directions. When the COM and COR are closer to each other, the eccentricity is minimized, which reduces torsional effects and drift.

The COM and COR for the existing lateral system are shown in Figure 48. Eccentricity exists only in the X-direction and is minimal at a distance of 5'.

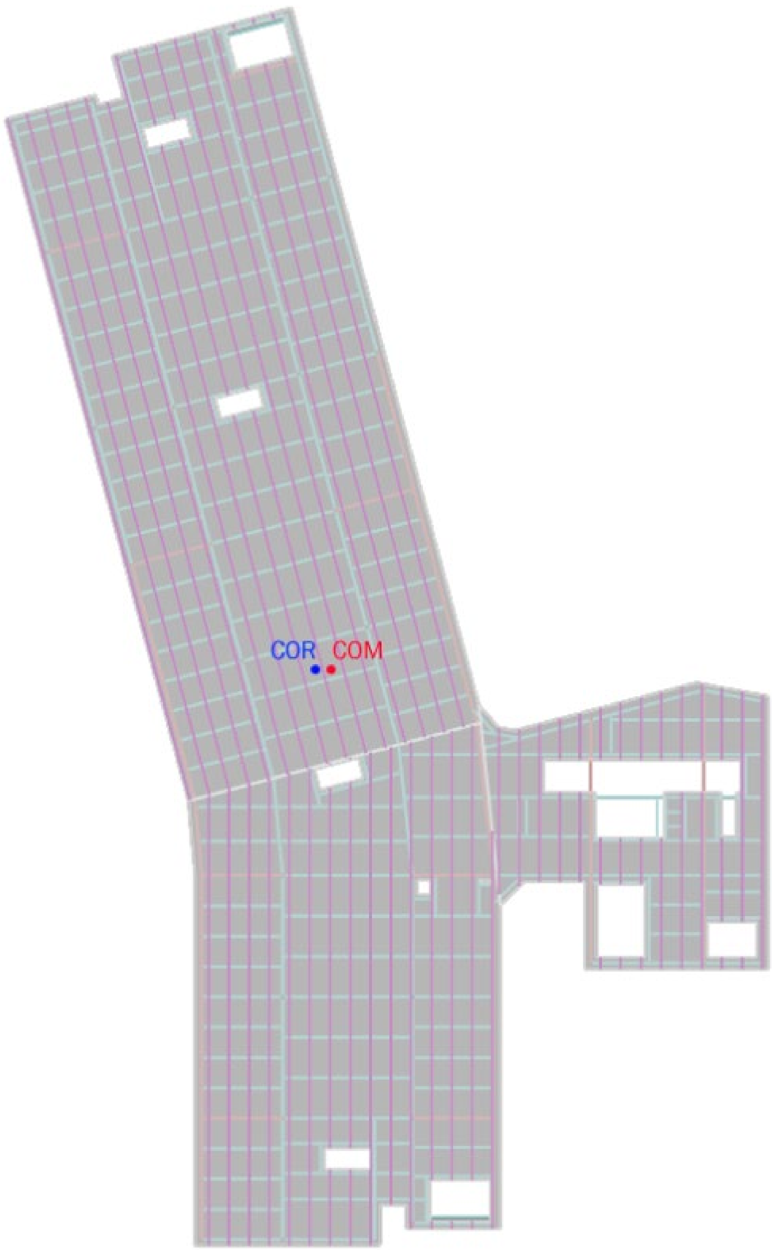


Figure 48: Existing Lateral System COM and COR

For the modified lateral system, ETABS was used to create a simplified model of the diaphragms and shear walls. Gravity members are not included in the model. Each slab is modeled as a deck with a rigid diaphragm. The deck properties are shown in Figure 49.

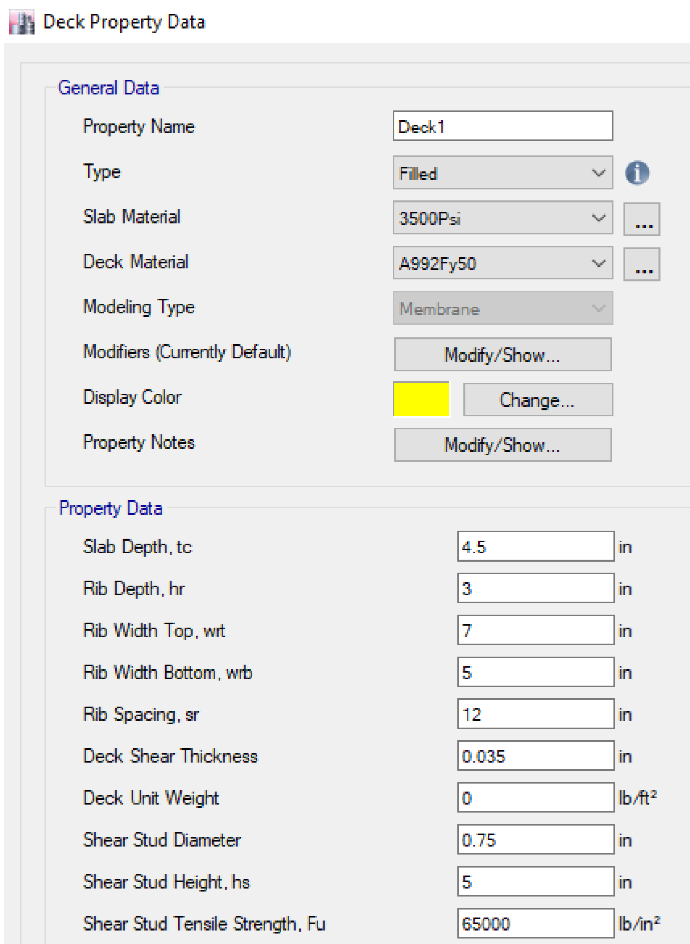


Figure 49: ETABS Deck Property Data

The shear walls were all modeled with the same strength and section properties, but wall sections vary in thickness from 8", 10", and 12". The locations considered for shear wall placement in the bed tower are shown in Figure 50. These locations include stair towers, elevator cores, and existing braced frame locations; however, some of these were not continuous throughout the entire structure. Some stairs are offset or change locations at the D&T levels, so they were not considered for potential shear wall locations. The goal was to maintain the architectural integrity of the building and preserve the patient-centered healing environment. This involved avoiding shear walls along the perimeter of the building so that natural light provided to the patient rooms was maximized.

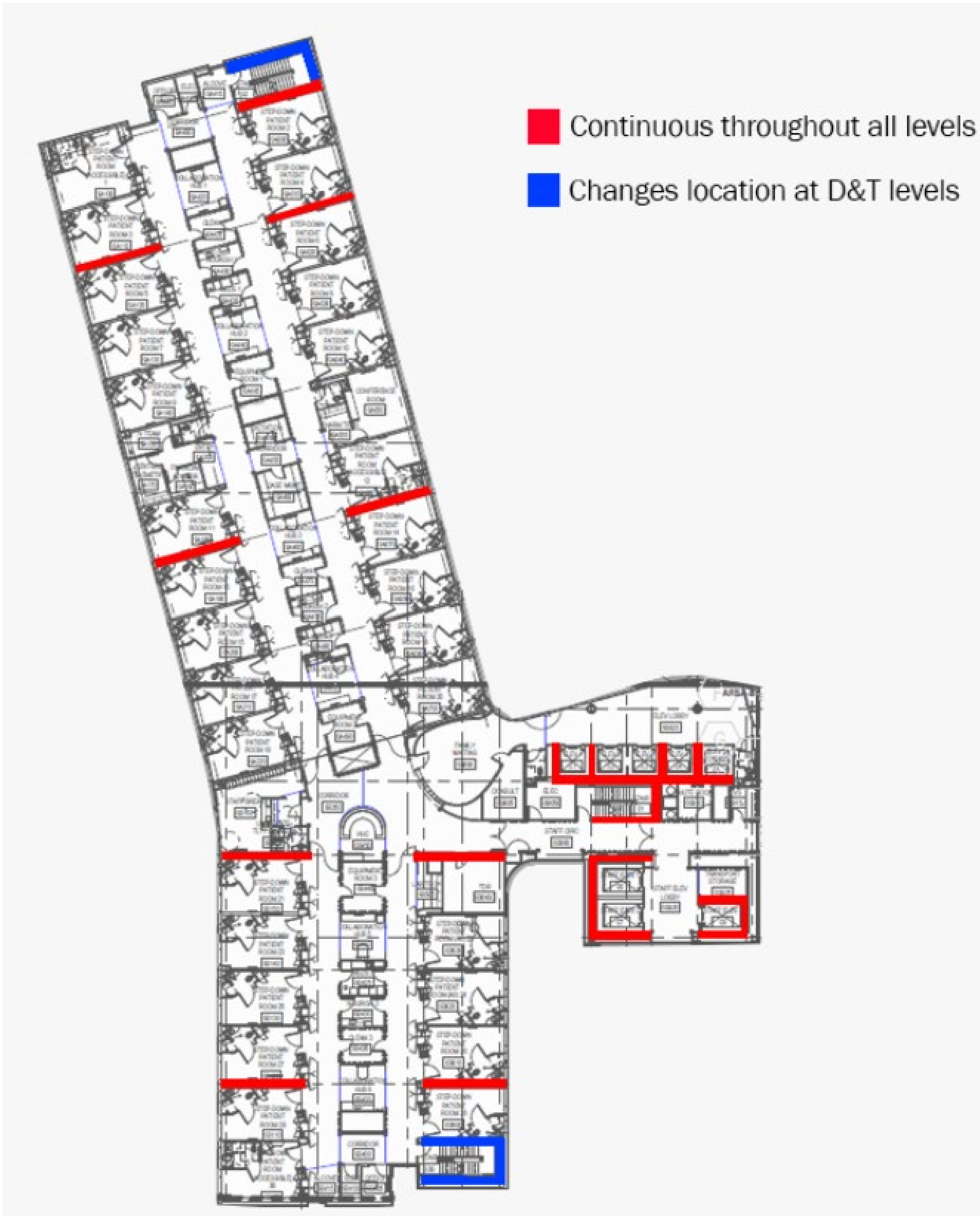


Figure 50: Potential Shear Wall Locations in Bed Tower

Many different iterations were tested in an effort to minimize the distance between COM and COR. The final iteration, shown in Figure 51, resulted in the closest COM and COR and is the starting point for designing the shear walls in RAM SS when incorporated into the fully modeled gravity system. At typical bed tower levels, the only eccentricity present is in the Y direction with a distance of 6.8'. A 3D view of this preliminary shear wall layout is shown in Figure 52.

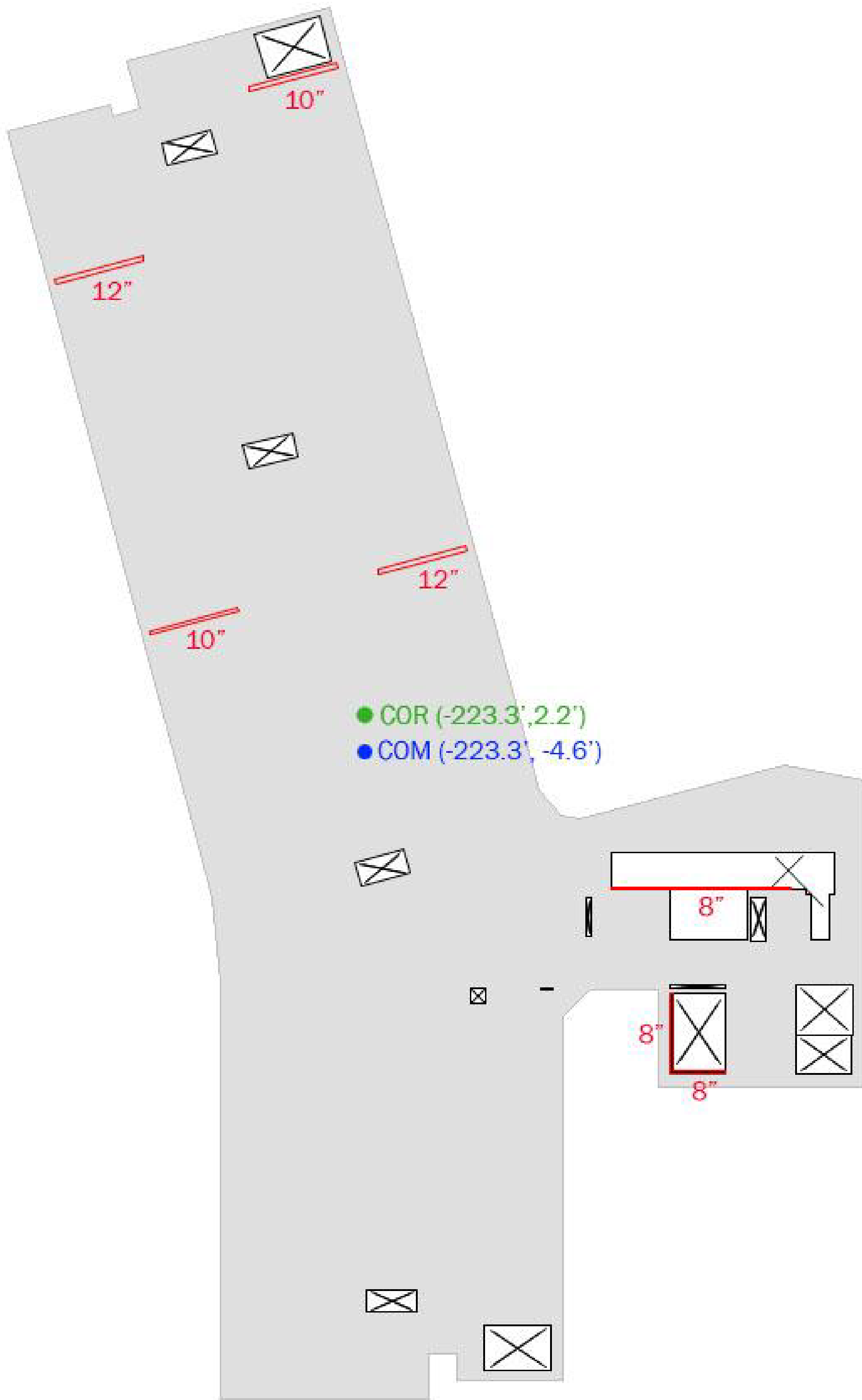


Figure 51: Preliminary Bed Tower Shear Wall Locations

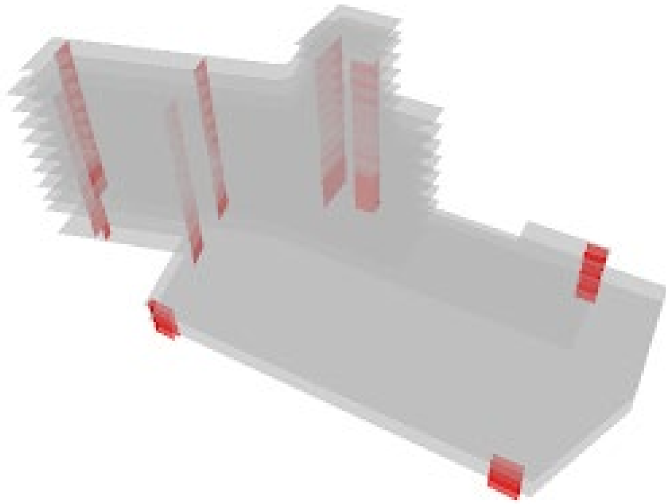


Figure 52: 3D View of Preliminary Shear Wall Locations

The next step was modifying the existing RAM SS model to replace the braced frame/moment frame system with the shear wall system. All lateral columns and beams were changed to gravity members, and the braces in the braced frames were deleted. The shear walls were then modeled in the locations determined from the ETABS study. They were initially modeled with full section properties and a strength of 4 ksi. After analyzing this iteration, the story drifts were checked. They exceed the H/240 drift limit, so the system had to be modified.

Since all of the structural members were not modeled in ETABS, the masses and stiffnesses were not accurately accounted for; therefore, the COM and COR were different and more offset when the shear walls were analyzed in RAM, causing considerable torsional effects. Modifications to the shear wall layout were made to align the COM and COR. One modification was changing the thicknesses of some walls. Additionally, shear walls in the Y direction were added to the single wall along the elevator core in the X direction. This wall was also shortened because it had a large stiffness which was causing the COR to move further away from the COM. These modifications caused the COM and COR to be more aligned in the Y direction, but there was still a significant eccentricity in the X direction, requiring other adjustments.

A wall in the X direction was added to the L-shaped shear wall around the other elevator core. Because the eccentricity was still too large, secondary shear wall locations in the Y direction were considered. This posed challenges since the walls in this direction have many openings or are not continuous throughout the entire structure. The bed tower floors have repetitive layouts; however, the D&T levels are less consistent, and many walls are offset from the walls on adjacent floors. One interior wall in the Y direction was found to be almost perfectly aligned throughout the entire building. Although some walls may need to be moved slightly, this was considered the best location since it would not drastically impact the architectural integrity. This reduces the design flexibility in this location, though, and may pose challenges for future changes or renovations. The wall location on the D&T levels and a typical bed tower floor is shown in Figures 53, 54, and 55.

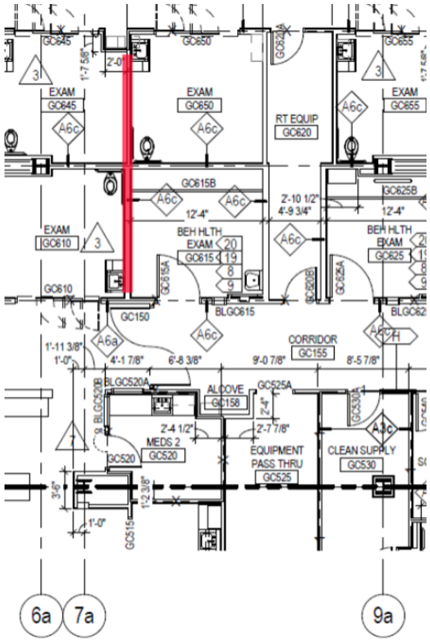


Figure 53: D&T Level 1 Shear Wall Location

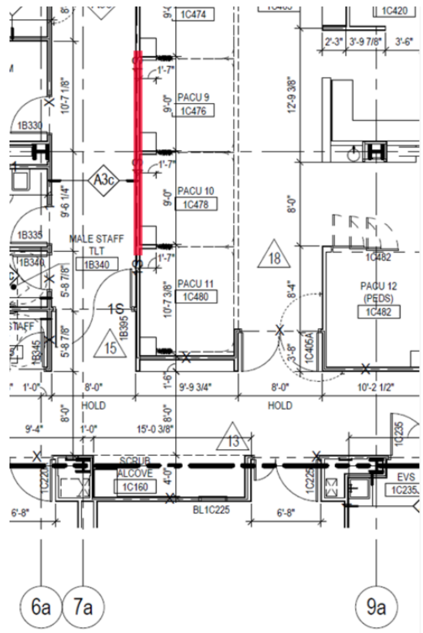


Figure 54: D&T Level 2 Shear Wall Location

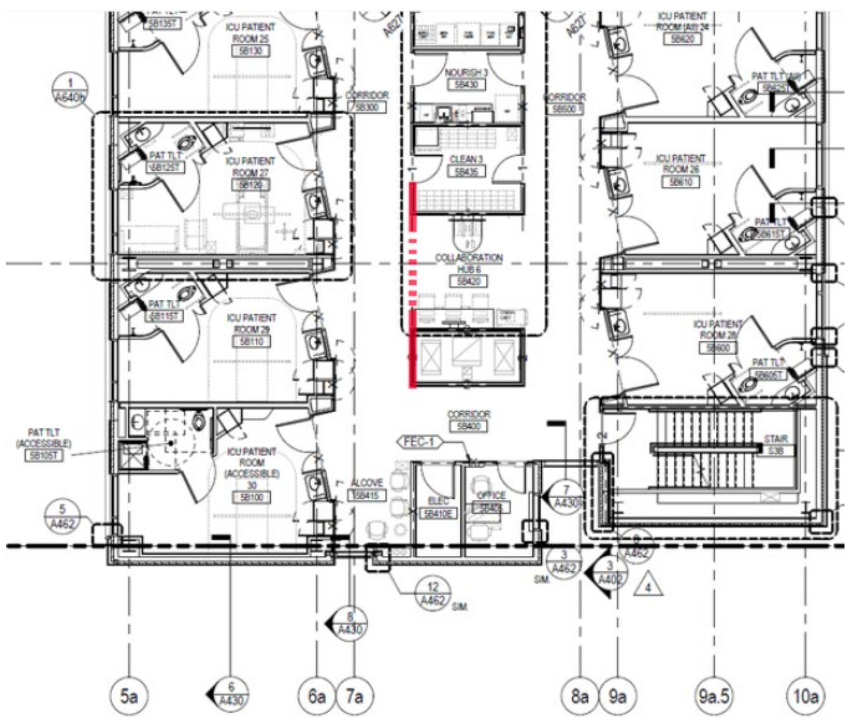


Figure 55: Typical Bed Tower Level Shear Wall Location

Figure 56 shows a building section highlighting the existing wall locations to be used for the proposed shear walls on the D&T levels and a typical bed tower floor. Since the walls are only slightly offset, it is reasonable to believe that they may be adjusted accordingly so that the wall can be continuous throughout the entire structure. It would be more logical to move this wall at the lower levels, marginally reducing the size of two PACU bays and two exam rooms.

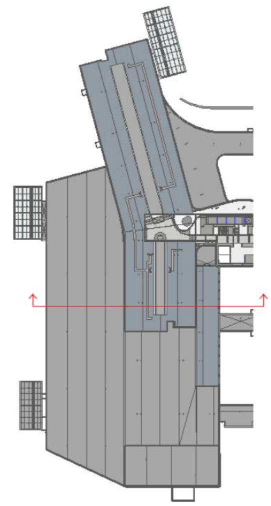


Figure 56: Building Section with Proposed Shear Wall Location

At the bed tower levels, this wall extends along a mechanical shaft and a collaboration hub. The collaboration hub has large openings so that the staff can easily access the area and move between patient rooms. An elevation of this wall is shown in Figure 57.

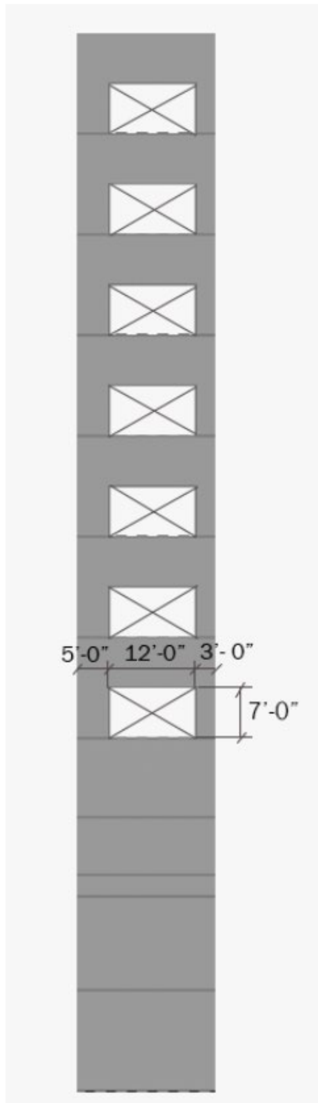


Figure 57: Shear Wall Elevation

Though this wall is not in an ideal location, it is the most reasonable location for an additional shear wall in this direction and serves to shift the COR closer the COM. The final COM and COR locations are shown in Figure 58.

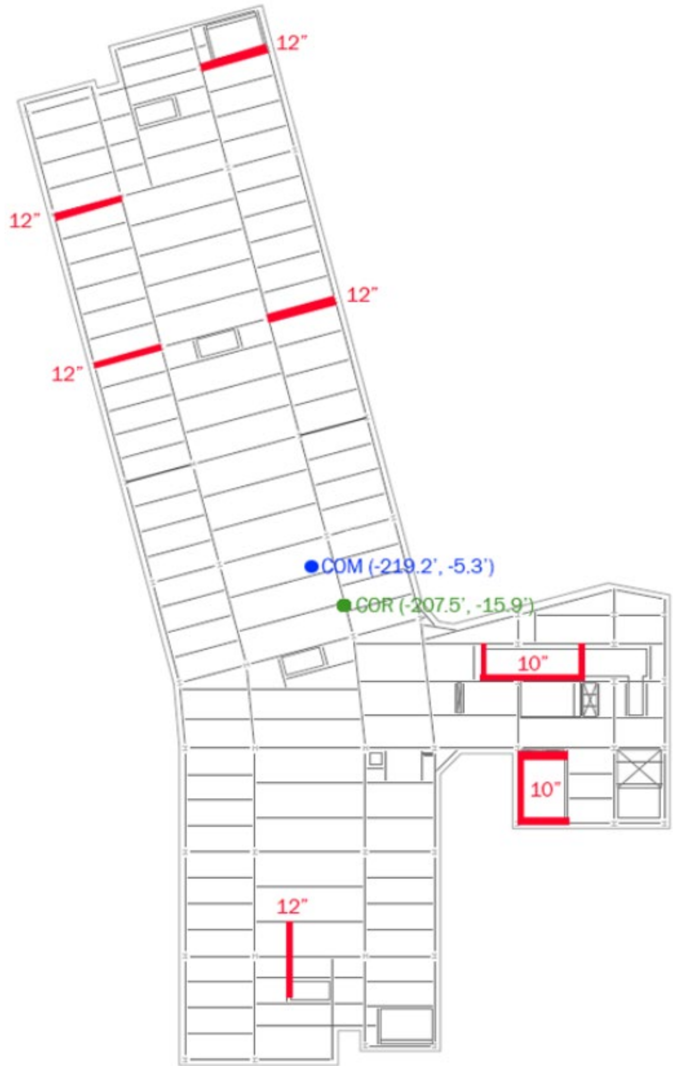


Figure 58: Final COM and COR Locations

The model was then analyzed to see if drift allowances were met. The walls were analyzed for an uncracked condition with a 0.7 cracked section factor for I (member) in RAM. In order to meet the story drift requirements, the wall strength must have an f'c of 8 ksi. It would be another option to use a lower strength concrete, but this would require increasing wall thicknesses. This was decided against as it may compromise the architectural integrity by reducing usable space. It was also determined that the cost of a higher strength concrete was minimal in comparison to the tradeoff of using lower strength concrete and greater wall thicknesses.

The final story drifts are shown in Figures 59 and 60. The second displays the story drifts when the model is analyzed for P-delta, which considers second-order effects. This causes the drifts to increase, but both analyses result in story drifts that are below the H/240.

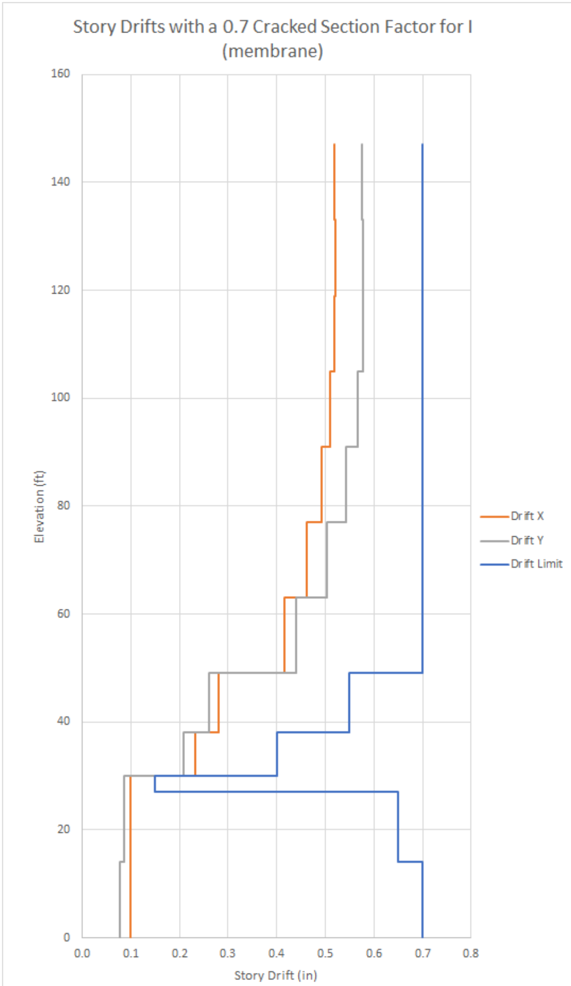


Figure 59: Story Drifts with a 0.7 Cracked Section Factor

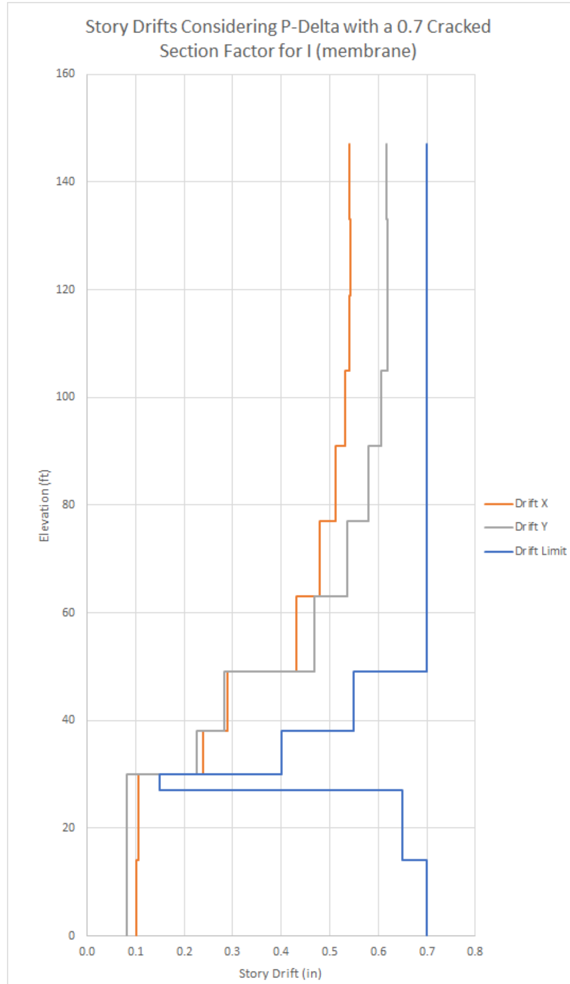


Figure 60: Story Drifts Considering P-Delta with a 0.7 Cracked Section Factor

A final serviceability analysis was run using a cracked section factor of 0.35 for the first two (D&T) levels of walls that extend the entire height of the structure. This is to account for any cracking that may occur since this is the area of the highest shear and moment forces in the walls. The resulting total lateral displacements shown in Figure 61 are below the H/240 limit.

Finally, the shear wall reinforcement was designed in RAM and verified with hand calculations. The section cuts used for verification are shown in Figure 62. Section cuts are taken at the bottom of the indicated walls.

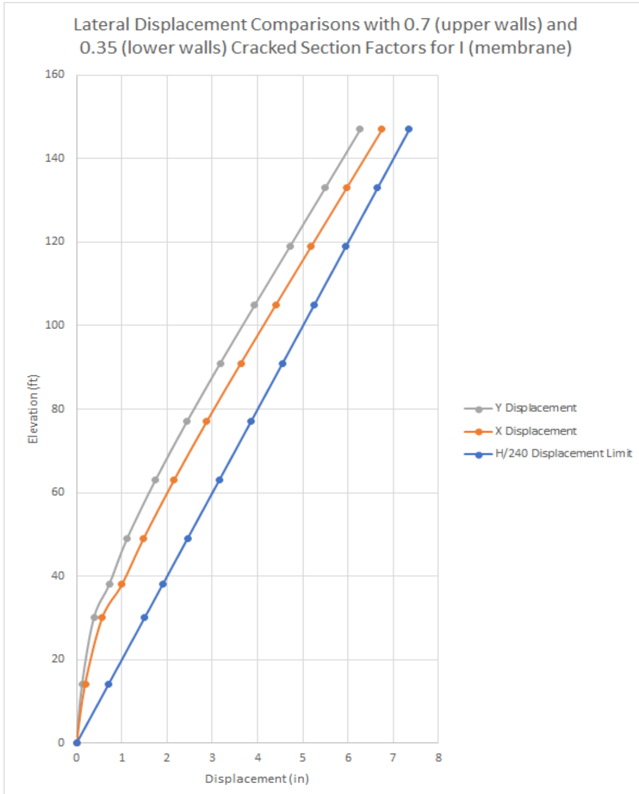


Figure 61: Lateral Displacement Comparisons with 0.7 and 0.35 Cracked Section Factors

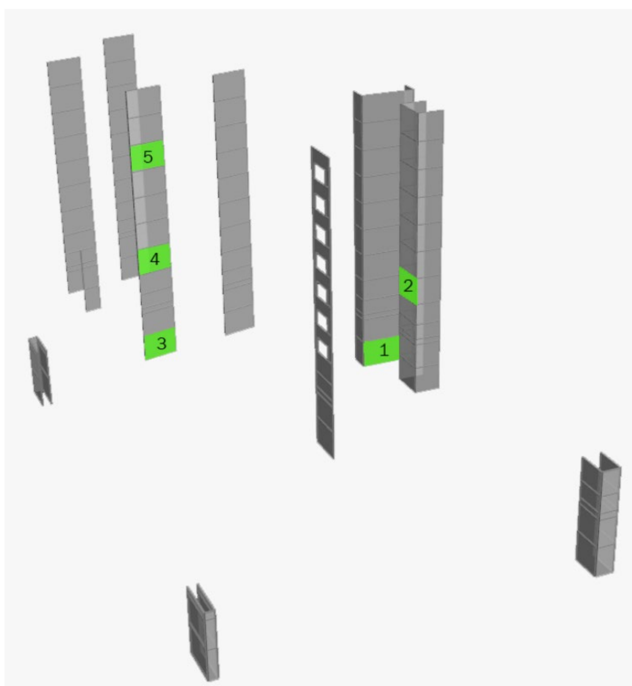


Figure 62: Shear Wall Section Cut Locations

Shear strength and reinforcement are verified with the following equations:

$$\emptyset V_n \geq V_u$$

$$\emptyset V_n = 0.75\,(V_c + V_s)$$

$$V_c = 2\sqrt{f'_c}hd$$

$$h = wall\ thickness\ (in)$$
$$d = 0.8l_w$$
$$l_w = wall\ length\ (in)$$

$$V_s = \frac{A_v f_y d}{s_h}$$

$$V_n \leq 10\sqrt{f'_c}hd$$

$$horizontal\ \rho_t: \rho_t = \frac{A_v}{s_h h}$$

$$\rho_t \geq 0.0025$$

$$s_h \leq min\begin{cases}\frac{l_w}{5}\\3h\\18"\end{cases}$$

$$horizontal\ \rho_l: \rho_l = \frac{A_v}{s_v h}$$

$$\rho_l \geq max\begin{cases}0.0025\\\left[0.0025 + 0.5\left(\frac{2.5 - h_w}{l_w}\right)\right](\rho_t - 0.0025)\end{cases}$$
$$h_w = wall\ height\ (in)$$

$$s_v \leq min\begin{cases}\frac{l_w}{3}\\3h\\18"\end{cases}$$

Detailed calculations for shear wall verifications are included in Appendix A. A summary of the results is shown in Table 16.

Table 16: Shear Wall Design Summary					
Section Cut #	*1*	*2*	*3*	*4*	*5*
Horizontal rft	#9 @ 6"	#9 @ 12"	#4 @ 12"	#4 @ 12"	#4 @ 12"
Vertical rft	#9 @ 6"	#9 @ 12"	#10 @ 12"	#4 @ 6"	#4 @ 12"
M_u (k-ft)	131,842	72,400	26,302	10,000	1733
V_u (k)	1113	840	415	194	77
$ØV_n$ (k)	1833	1213	597	597	597

All walls meet the shear strength, reinforcement, and spacing requirements. This check verifies the RAM shear wall design results. 3D views of the entire structure and final shear wall system are shown in Figure 63.

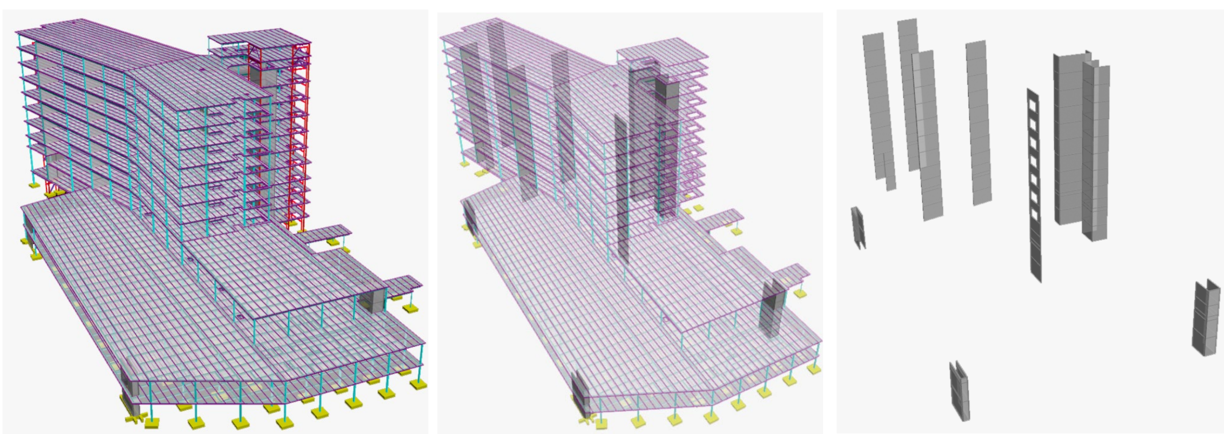


Figure 63: Redesigned Structural Systems Modeled in RAM SS

This shear wall system is recommended for use in the structure in the Fort Lauderdale location or other similar hurricane regions. It is effective in reducing drifts, but further studies would be useful to further minimize the torsional effects created by eccentricity between the COM and COR. Multi-criteria decision-making methods would be useful for choosing between alternative lateral system concepts. In this case, it was determined that shear walls were the most appropriate option as it would not be feasible to increase member sizes in the braced and moment frames enough to meet drift requirements. Therefore, the decision-making methods were note applied to the lateral system redesign, but they could be applied if multiple iterations of the shear wall system were being considered.

10.0 Structural Depth Overview

10.1 Existing and Redesigned System Comparisons

The existing Mercy Health Muskegon medical center has composite steel gravity system and a later system composed of moment frames and braced frames. The redesigned gravity structure is non-composite steel that maintains that original framing layout. The redesigned lateral structural eliminated all braced and moment frames and utilizes concrete shear walls. The existing and redesigned structural systems were compared for cost (material, labor, and equipment), construction labor hours, and weight. The comparisons are shown in Figures 64-68.

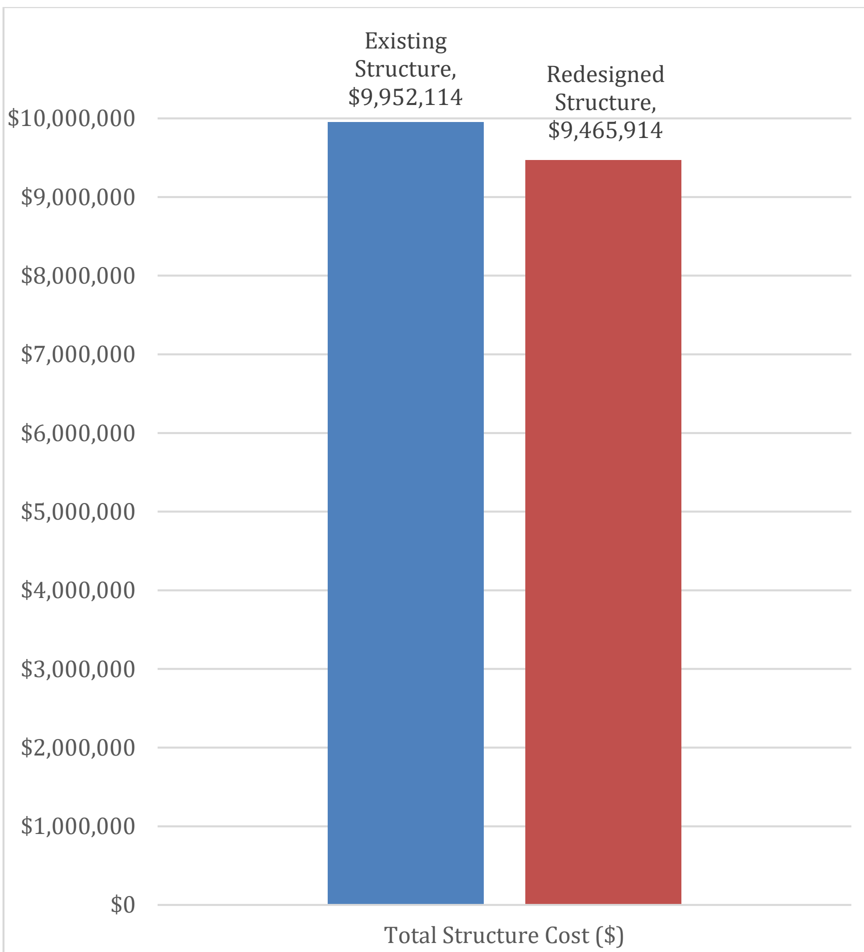


Figure 64: Structural Cost Comparison

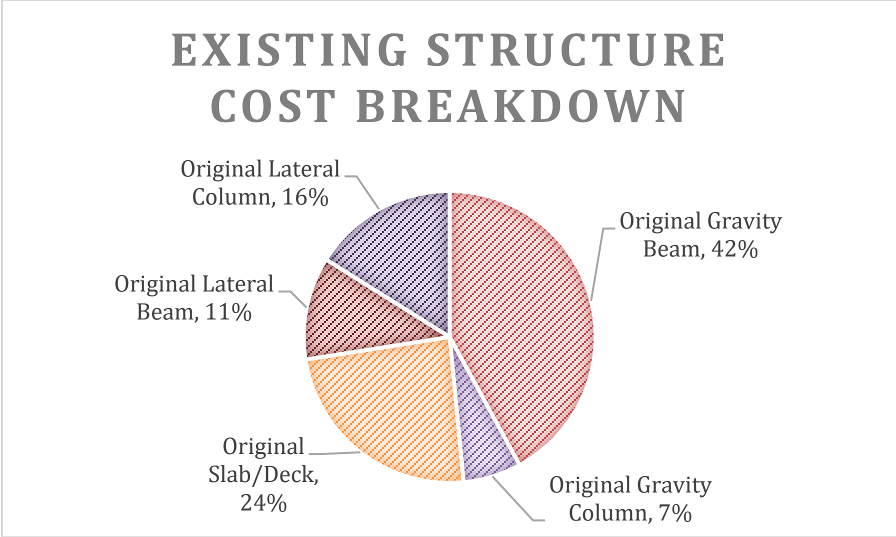


Figure 65: Existing Structure Cost Breakdown

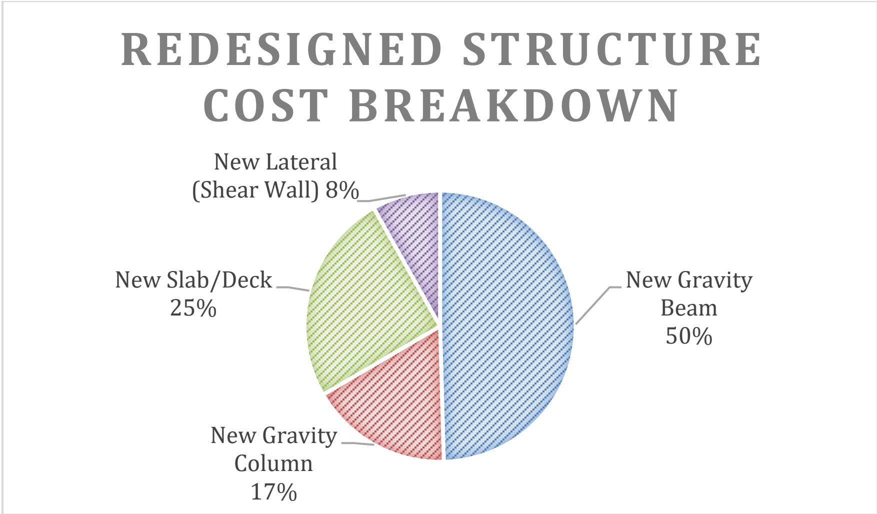


Figure 66: Redesigned Structure Cost Breakdown

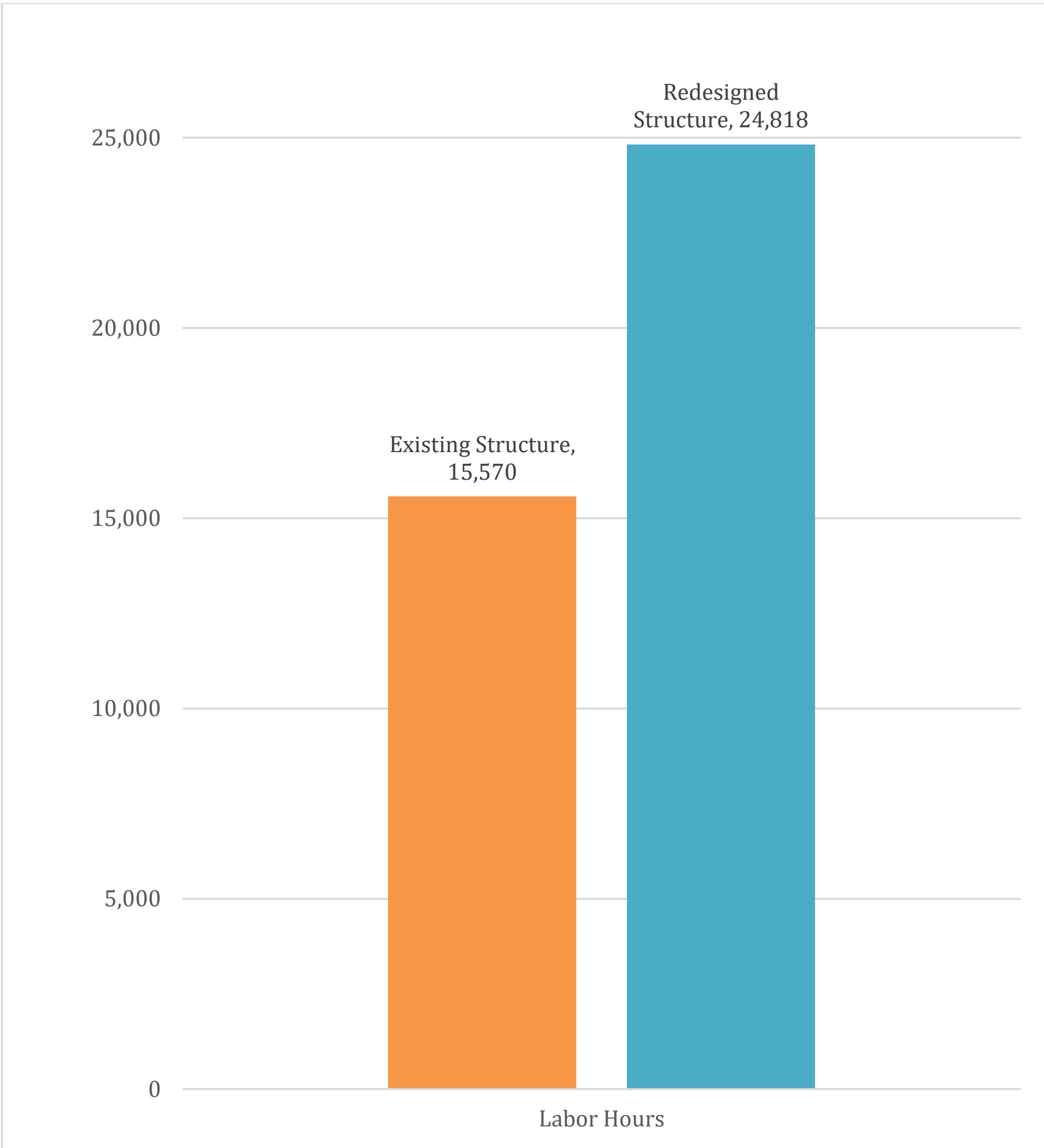


Figure 67: Labor Hour Comparison

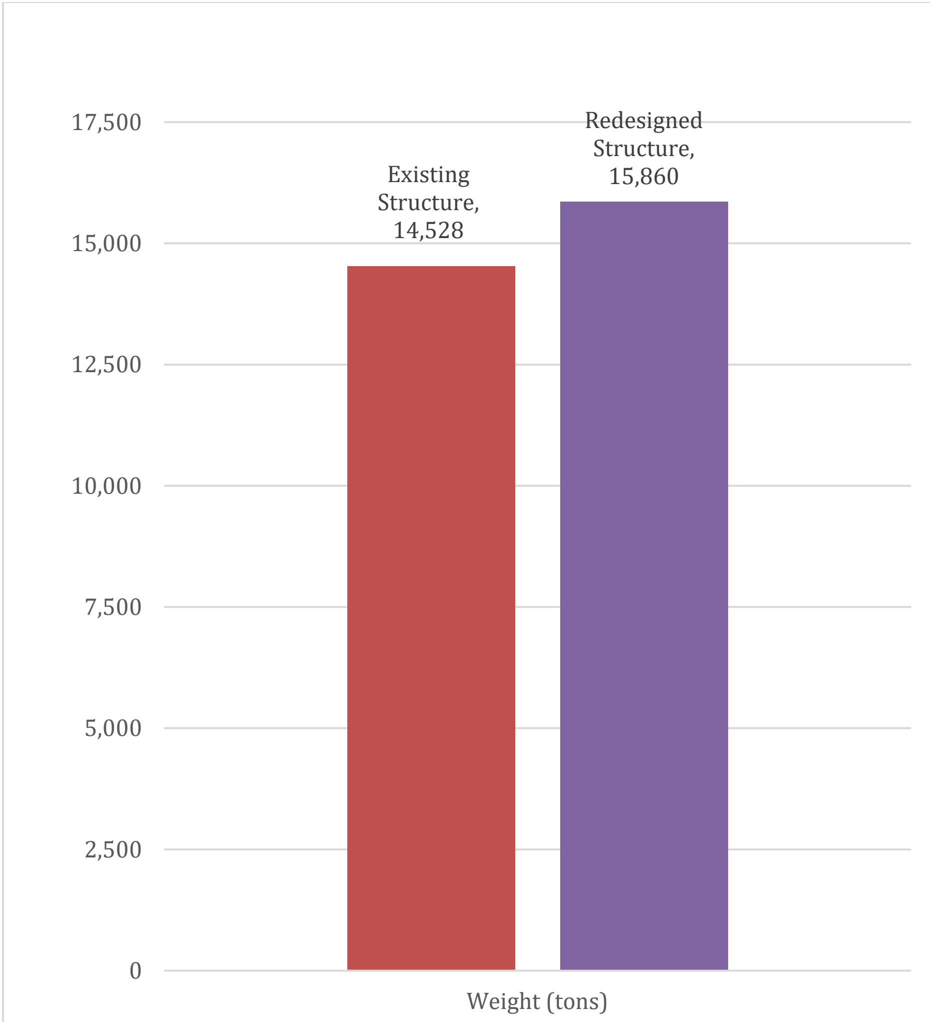


Figure 68: Structural Weight Comparison

The results show that the redesigned system reduces cost by approximately $500,000. This is largely due to the reduced costs associated with the use of shear walls instead of sizable column sections required for the lateral frames. A downside to the use of shear walls is the additional time required for construction. The amount of labor hours for the redesigned system is considerably higher since concrete takes longer to shore, place, and cure than steel erection. The concrete also adds additional weight to the structure. For the Fort Lauderdale location, the redesigned non-composite steel system with concrete shear walls would be recommended because it has better vibration and drift performances as well as a lower cost than the composite steel and lateral frame system.

10.2 MAE Requirements

MAE requirements are satisfied by the application of advanced computer modeling techniques. The applied techniques expand upon those learned in the graduate course AE530: Computer Modeling of Building Structures. The course discussed techniques such as modeling braced frames, moment frames, shear walls, and diaphragms and applying loads in ETABS. These methods were used to model both the existing and redesigned lateral system in ETABS.

These techniques were also applied to other computer modeling programs outside the scope of AE530. Similar methods were used to understand the techniques and constraints for modeling systems in RAM Concept and RAM Structural System.

RAM Concept was used to model the flat slab system discussed in Section 6.2. The original flat slab thickness was based on a conservative value permitted by ACI that allows a deflection check to be neglected. A more accurate thickness was determined by modeling a typical floor in RAM Concept and running several trial analyses. Modeling techniques similar to those discussed in AE530 were used to model the floor, apply loads, and understand results. The model is shown in Figure 69.

Figure 69: Plan View of RAM Concept Model

The initial model uses the thicknesses used for the original alternative gravity bay study. The slab thickness was 12" with 8" drop panels. Interior columns were 17"x17" and exterior columns were 20"x20". All concrete was 4 ksi normal weight concrete. Figure 70 shows the live load deflection, total load deflection, and punching shear check.

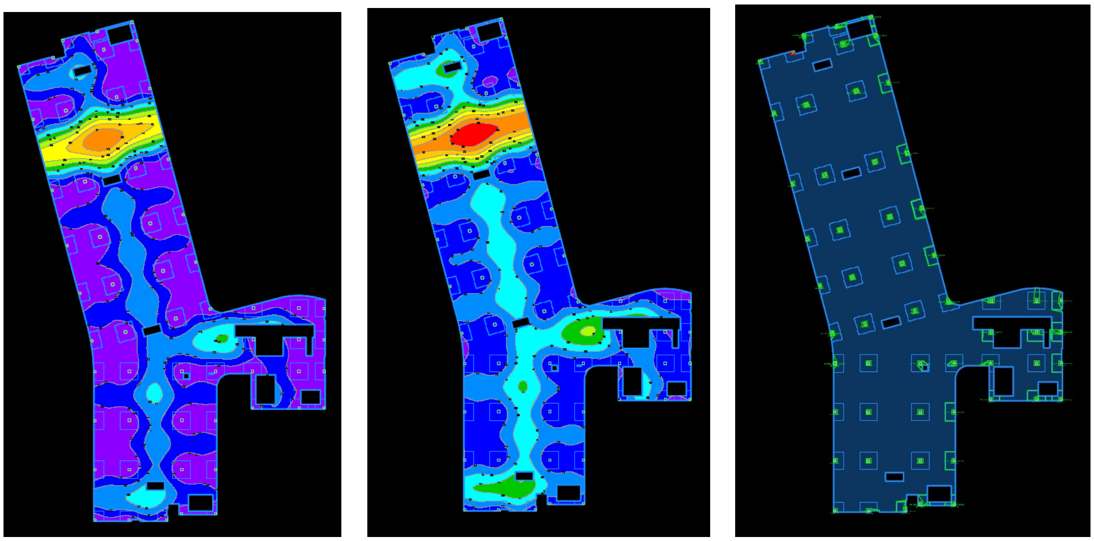


Figure 70: Initial Live Load Deflection, Total Load Deflection, and Punching Shear Check

The deflections were checked against LL and TL deflection limits of L/240 and L/360 or 1", whichever is lower. All deflection and punching shear requirements were met. Other trials were run to determine more accurate thicknesses that had deflections closer to the allowable limit. While some assumed a uniform thickness across the floor, others used a different thickness for the critical span of 45' that had significantly higher deflections than the remainder of the floor. The final deflections and punching shear check are shown in Figure 71.

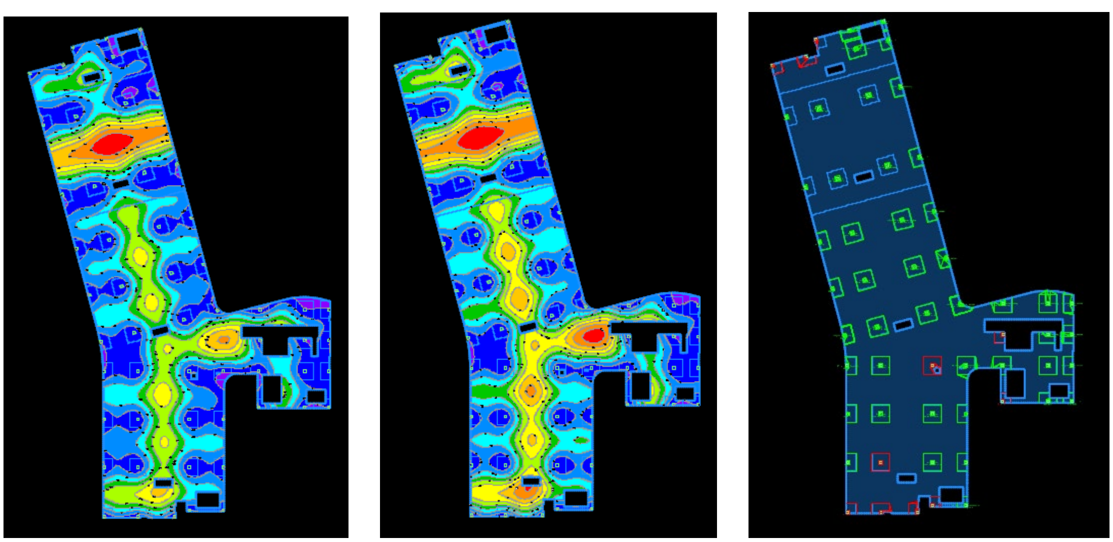


Figure 71: Final Live Load Deflection, Total Load Deflection, and Punching Shear Check

The final design includes an 8" slab with 4.25" drop panels and an 11" slab and 8" drop panels in the 45' span. The maximum structural depth would be 19", which is similar to the 20" maximum depth used in the preliminary alternative gravity bay study. The interior columns are 17" square columns and the exterior columns are 20" square columns. Several of the columns around slab edges or openings had punching shear issues, but since this was used for conceptual design comparisons and not as a detailed final design, these issues were not further analyzed. The deflection results of all the RAM Concept iterations are included in Appendix A. Overall, the understanding of AE530 modeling techniques was transferred over and applied to modeling the flat slab system in RAM Concept to gain a more appropriate slab thickness.

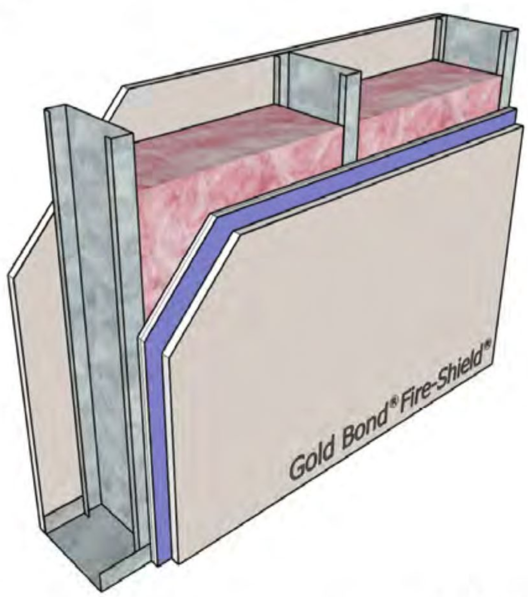
Similarly, AE530 modeling techniques were also used to model the existing and redesigned gravity and lateral systems in RAM Structural System. The methods were used to analyze and redesign the entire structure. In additional to these typical methods, the redesign also used the vibration analysis tool in RAM SS. This required further research that went beyond the analysis techniques discussed in AE530.

11.0 Acoustics Breadth

While the structural system redesign focused on patient wellbeing through vibration performance, this study centers on promoting a healing environment through acoustic performance. Two areas that are dedicated to patient care and healing will be analyzed and suggestions for improvement will be made if necessary. These areas include a typical patient room and patient bays in the post anesthesia care unit (PACU).

11.1 Patient Room Acoustic Analysis

Patient rooms in the bed tower are typically separated with 1hour fire-rated partitions composed of 6” 20-gauge minimum metal studs at 16” o.c. and full height insulation of the same thickness as the studs. There is one layer of 5/8” gypsum board on one side and two layers of 5/8” gypsum board on the other side. This is considered a two-leaf panel. It is important to have two layers of gypsum board and only one on the other because the dissimilar thicknesses cause the two sides to have different coincidence frequencies. If they are the same thickness and material, there will be larger coincidence dip and poor acoustic performance.



STC-49	NGC 2013024
Framing:	6" steel studs, **20 gauge**, 16" o.c.
Insulation:	6" glass fiber
Side 1:	5/8" Fire-Shield Gypsum Board
Side 2:	5/8" Fire-Shield Gypsum Board on 5/8" SoundBreak XP Gypsum Board
UL Design:	V438, U465 - 1 hour

Figure 72: Patient Room Partition Assembly (National Gypsum)

The project specifications state that one-hour drywall construction must have a minimum STC rating of 47. The specifications also provide a list of acceptable gypsum manufacturers that includes National Gypsum Company, which will be used as a reference for the wall assembly STC rating. A sample wall assembly from the National Gypsum Company Acoustical Assembly Guide is shown in Figure 72. This accurately represents the patient room partition assembly. The assembly has an STC rating of 49, which is above the minimum required by the specifications. Additionally, Table 17 from *Design Guidelines for Health Care Facilities (2010)* recommends STC 45 for horizontal separation between patient rooms. This standard is met by the patient room partition with an STC of 49. Therefore, the partitions between typical patient rooms meet the acoustics standards and do not need to be reevaluated.

Table 17: Recommended Healthcare STC Values

Adjacency combination		STC_c
Patient Room	Patient Room (horizontal)	45[1]
Patient Room	Patient Room (vertical)	50
Patient Room	Corridor (with entrance)	35[2]
Patient Room	Public Space	50
Patient Room	Service Area	60[3]
Exam Room	Corridor (with entrance)	35[2]
Exam Room	Public Space	50
Toilet Room	Public Space	45
Consultation Room	Public Space	50
Consultation Room	Patient Rooms	50
Consultation Room	Corridor (with entrance)	35[2]
Patient Room	MRI Room	60[3]
Exam Room	MRI Room	60[3]
Exam Room	Exam Room (no electronic masking)	50
Exam Room	Exam Room (with electronic masking)	40
Public Space	MRI Room	50

11.2 PACU Acoustic Analysis

The Post Anesthesia Care Unit (PACU) is a D&T area where patients are monitored after being given anesthesia. Though stays in the PACU typically last a few hours, others may be extended. Patients in the PACU often experience pain and must be closely monitored, so it is important to provide them a comfortable and accessible space. The existing PACU configuration consists of 19 bays shown in yellow in Figure 73.

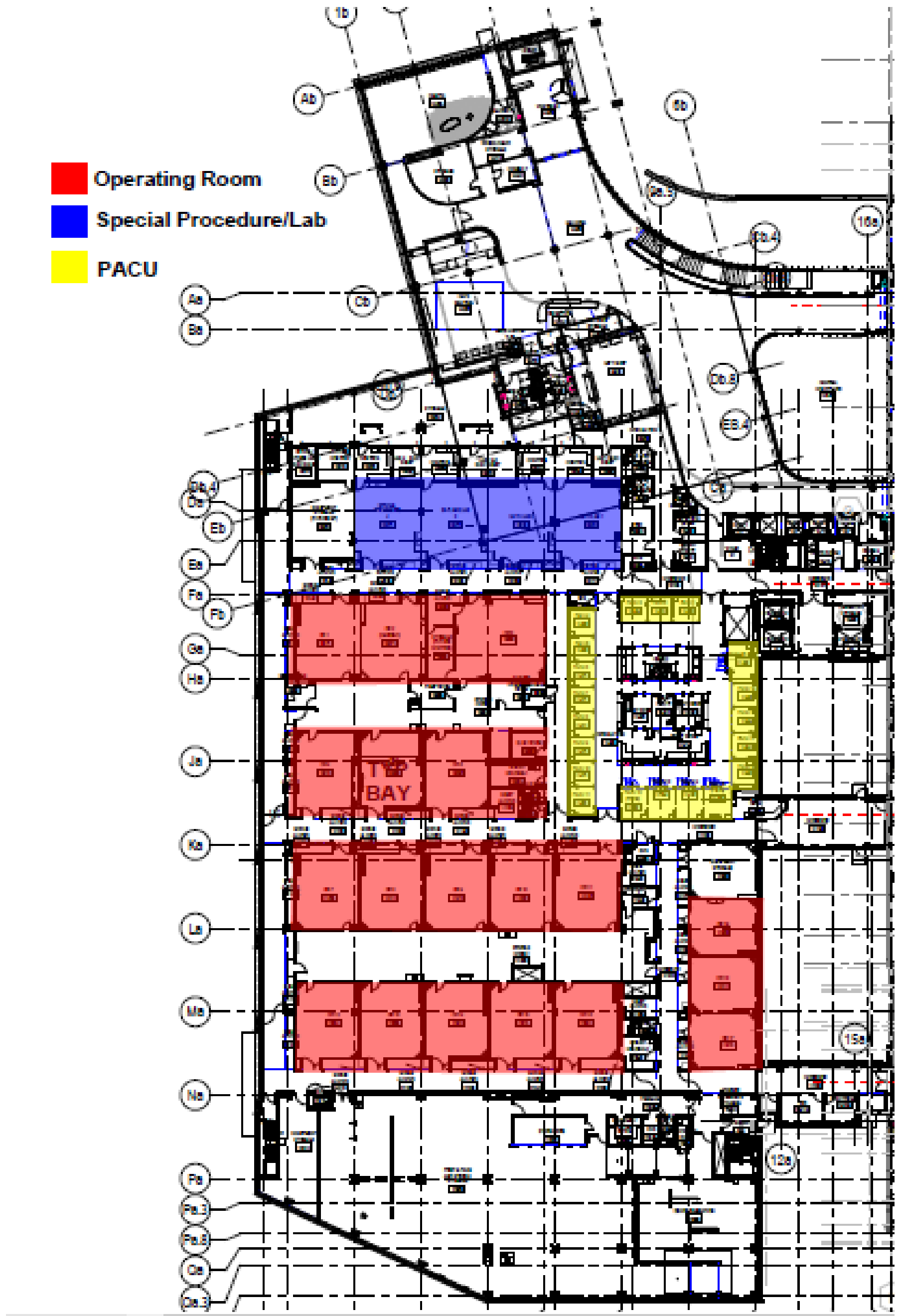


Figure 73: D&T Floor Plan with PACU Layout

Enlarged plans of PACU bays are shown in Figures 74 and 75.

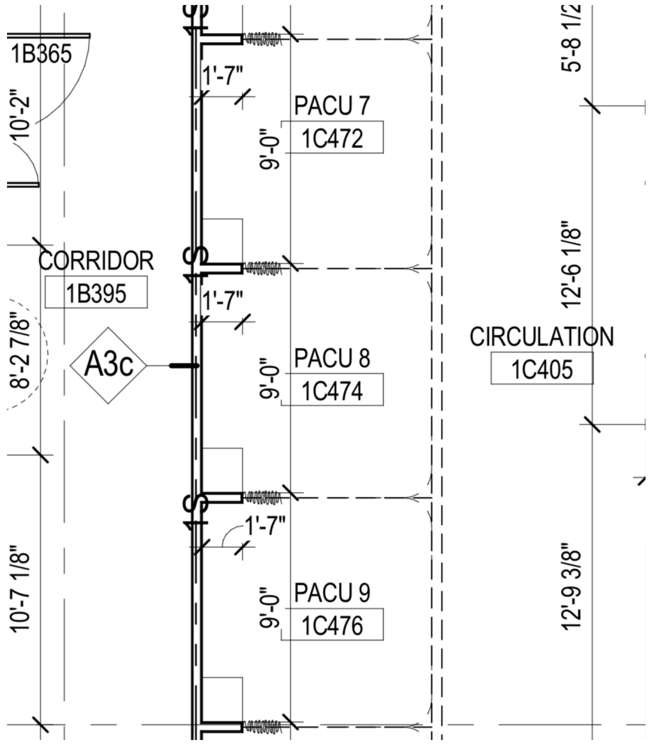


Figure 74: Adjacent PACU Bays

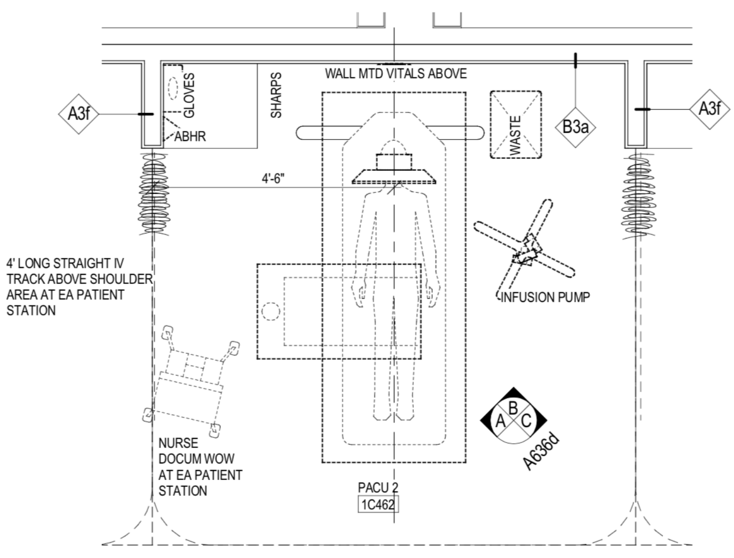


Figure 75: Enlarged PACU Plan

Currently, the only separation between PACU bays are polyester privacy curtains. There is a 1' space between the bottom of each curtain and the floor. While they provide convenient entries for nurses moving between patients, they provide practically no noise resistance. This is a concern for recovering patients who desire a quiet, relaxing environment.

A sample image of the existing privacy curtain (source: http://eykon.net/haven-59903) is shown in Figure 76. An image of the existing PACU layout with the privacy curtain separations is included in Figure 77.

Figure 76: Sample PACU Privacy Curtain (Eykon)

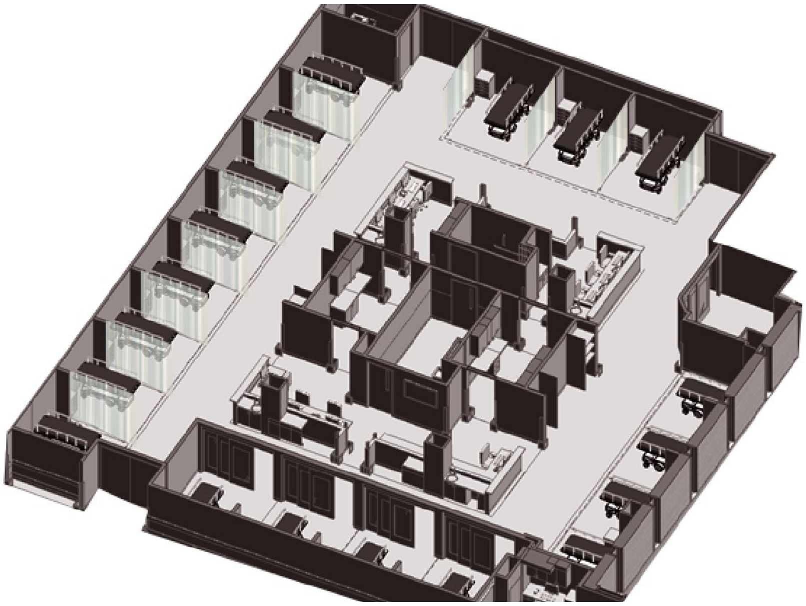


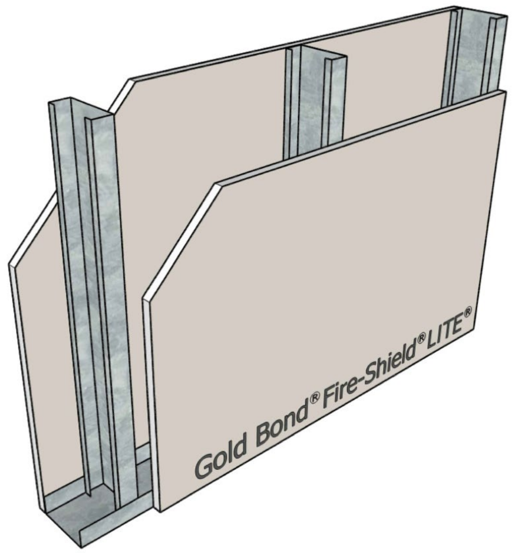
Figure 77: Existing PACU Layout

Acoustic accordion doors are one of the proposed alternate solutions to the issue of compromised comfort and speech privacy. Woodfold is a company that manufacturers several types of acoustic accordion doors with varying degrees of acoustic performance. An image of a Woodfold acoustic accordion door (source: https://woodfold.com/accordion/series-3300/) is shown in Figure 78. These doors are easily movable and provide privacy and an acoustic lining between rooms. It is also an option to use accordion doors in combination with the privacy curtains so that nurses can maintain privacy when the doors are not being used as acoustic separation.

Figure 78: Sample Acoustic Accordion Door (Woodfold)

Two options from Woodfold include the Series 2100 with an STC of 21 and the Series 3300 with an STC of 33.

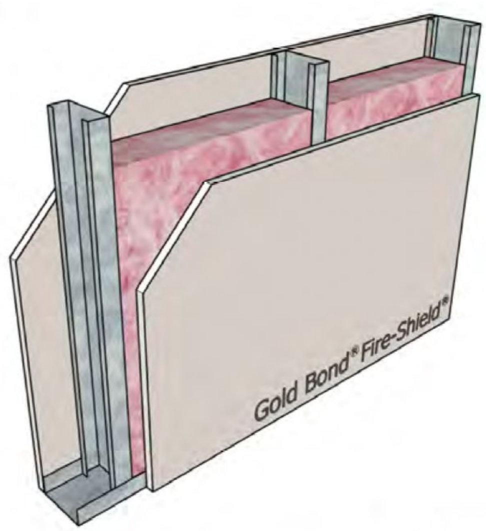
Other options include full height partitions. The existing walls that extend 1'-7" into the PACU bays are composed of 3-5/8" 20-gauge metal studs at 16" o.c. and one layer of 5/8" gypsum board on each side. An example of this assembly from National Gypsum Company is shown in Figure 79. The STC rating is 37. This same assembly with the addition of insulation is STC-40 as shown in Figure 80.



STC-37 **NGC 2014023**

Framing:	3-5/8" steel studs, **20 gauge**, 16" o.c.
Insulation:	None
Side 1:	5/8" Fire-Shield LITE Gypsum Board
Side 2:	5/8" Fire-Shield LITE Gypsum Board

Figure 79: Proposed PACU Partition with No Insulation (National



STC-40 **NGC 2013004**

Framing:	3-5/8" steel studs, **20 gauge**, 16" o.c.
Insulation:	3-1/2" glass fiber
Side 1:	5/8" Fire-Shield Gypsum Board
Side 2:	5/8" Fire-Shield Gypsum Board

Figure 80: Proposed PACU Partition with Insulation (National Gypsum)

The studs in this PACU assembly extend to the structure above and the gypsum extends 4" above the acoustic ceiling tiles. When the partition extends only to the ceiling, there is the potential for flanking. This means that sound has the ability to travel above the wall, through the plenum, and into the adjacent room. This can be controlled by extending the entire partition to the structure, which can pose issues with mechanical system integration. Another option is to provide insulation on top of the portion of the partition that extends above the ceiling.

The partition alternatives must be carefully considered. They may not be practical if used to separate every PACU bay as this would inconvenience the nurses who care for multiple patients and need to travel quickly between multiple bays. This would in turn decrease the provided standard of patient care.

A 2008 study written by Lenore Smykowski and published by the American Society of PeriAnesthesia Nurses poses an alternative solution to this issue. The study outlines the results of a redesigned PACU in the Memorial Sloan Kettering Cancer Center. After repeated complaints about noise and privacy, the PACU design was reimagined. The final design used pods of four patient bays with partitions between each pod. This provided the additional privacy and noise reduction for patients and families while allowing nurses to provide quality care. The study states that each nurse typically cares for two patients in the PACU, making each pod evenly staffed with two nurses. Overall, the results indicated that noise complaints dropped significantly, and safety and comfort was maintained for everyone in the PACU.

A similar solution can be used for the Mercy Health Muskegon PACU. While the existing layout does not allow for pods of four bays, there is an opportunity to create pods of two bays. This would allow one nurse to be staffed to each bay.

The existing PACU design for one wall of bays and two alternative solutions are shown in Figure 81. The design in the center includes pods of two bays separated by a privacy curtain. This would reduce noise from one adjacent bay and maintain accessibility for the nurses. The design on the right is a modified version of the pod format. The beds are rotated, and an additional wall is added along the corridor. While this provides for more acoustic separation between the patient and staff areas, it blocks sightlines to the patients and could make it more difficult to move beds in and out of the bays. Since the patient vitals are typically mounted above the patient's head, this configuration could also result in noise traveling through the walls if electrical outlets behind the beds are aligned. Staggering the outlets would minimize this occurrence.

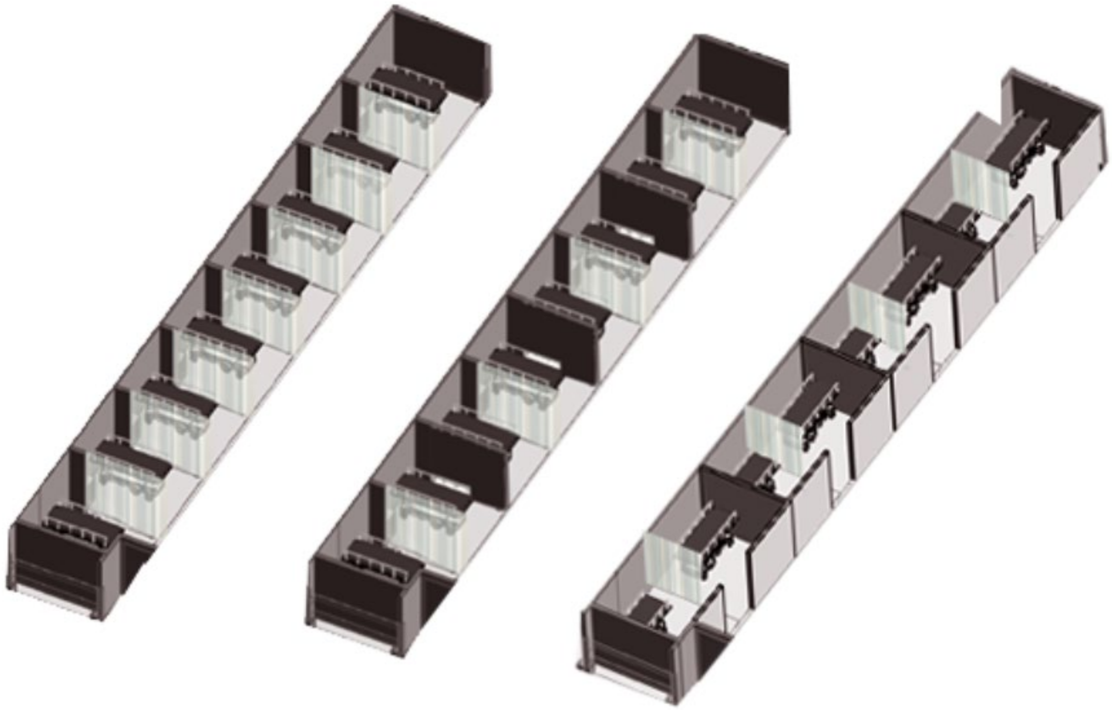


Figure 81: Existing and Potential PACU Layouts 1 and 2

The existing design and all of the alternative solutions have advantages and challenges. Cost estimates (Table 18) followed by a cost-STC comparison (Figure 82) were performed to see which alternative had the best combined performance in relation to these criteria.

Table 18: PACU Acoustic Solution Cost Estimates

	STC	Cost	Quantity Required	Total Cost
Privacy Curtain	0	$26/curtain	15 + 20 extra to owner	$ 910
Woodfold Series 2100	21	$1350/panel	15	$ 20,250
Woodfold Series 3300	33	$3300/panel	15	$ 49,500
Partition (no insulation), pod layout 1	37	$19.35/LF + $0.76/SF	75 LF/600 SF + 9 curtains	$ 2,141
Partition (with insulation), pod layout 1	40	$19.35/LF + $1.11/SF	75 LF/600 SF + 9 curtains	$ 2,351
Partition (no insulation), pod layout 2	37	$19.35/LF + $0.76/SF	220 LF/1750 SF + 9 curtains	$ 5,821
Partition (with insulation), pod layout 2	40	$19.35/LF + $1.11/SF	220 LF/1750 SF + 9 curtains	$ 6,434

	Partition Cost Data	
8' high, 3-5/8" studs @ 16" o.c.	$19.35/LF	
5/8" gypsum board, on walls, standard, no finish included	$0.76/SF	
Owens Corning sound attenuation batt 24"x96"	$0.35/SF	*Note: material cost only*

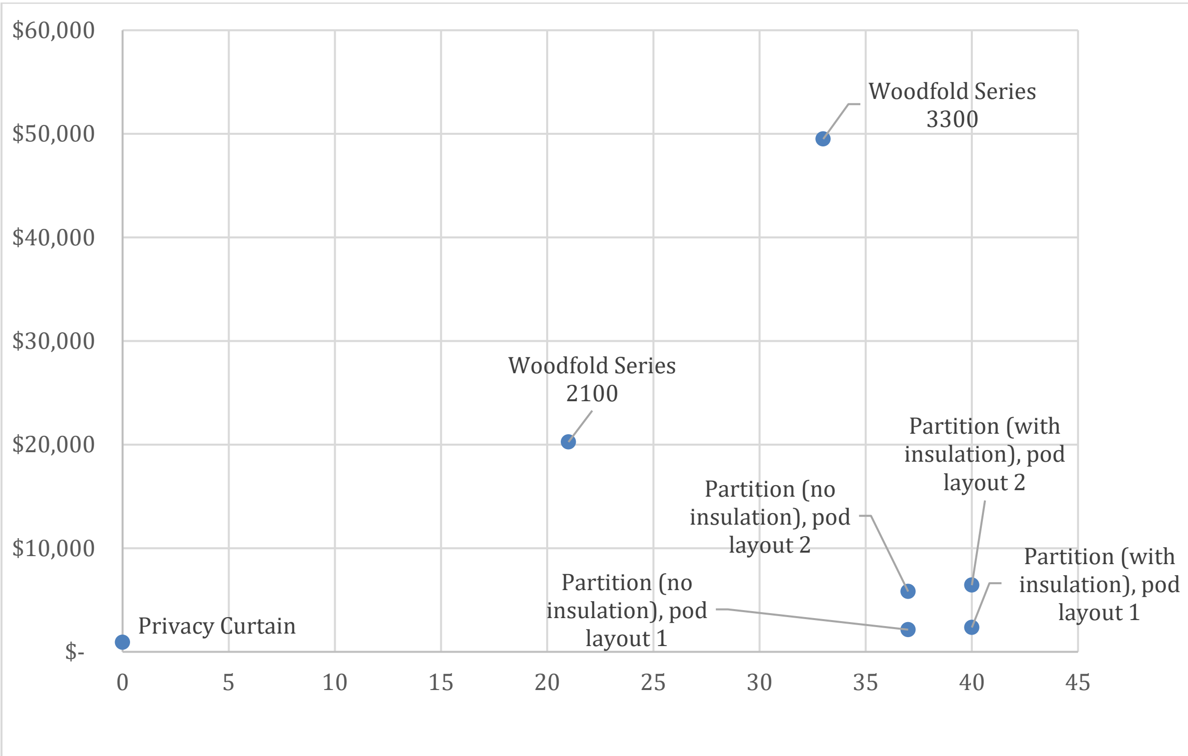


Figure 82: Cost – STC Comparisons for PACU Acoustic Solutions

The partition assembly with insulation and pod layout 1 has the highest STC rating and one of the lowest costs, but a disadvantage to this design is additional installation time. In comparison to the existing privacy curtain separations, this design provides improved acoustic performance and additional privacy. The pod layout also provides a level of separation that does not inconvenience nurses or reduce safety, but it may require adjustment for nurses who are accustomed to a typical PACU layout. Due to mechanical conflicts, the partition cannot be extended to the structure. To avoid flanking, the recommendation is to extend the partition 4" above the ceiling and top with fiberglass insulation that extends 4' from the partition on both sides (see Figure 83).

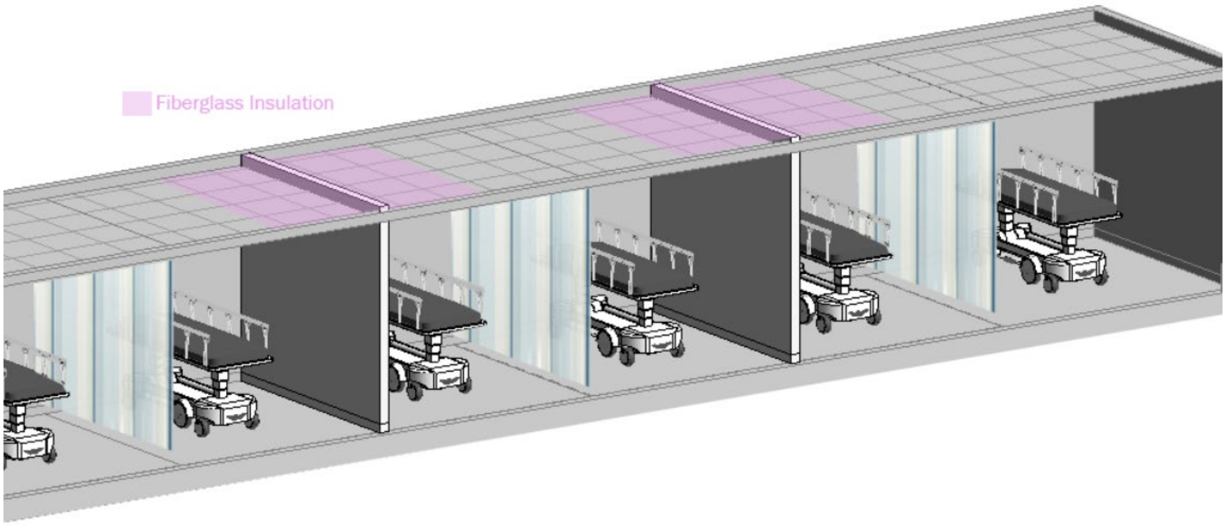


Figure 83: Recommended PACU Acoustic Design Solution

Overall, a pod system that implements insulated partitions will provide the most benefits for acoustic performance and privacy without jeopardizing a high level of patient care.

12.0 Prefabrication Breadth

Prefabrication is becoming more common in healthcare facilities due to pressure for shorter construction timelines. While prefabrication requires more planning from the beginning of a project to maximize benefits, it can reduce construction schedules and lead to cost savings for the owner by allowing the hospital to be occupied earlier and produce income. Prefabrication also results in higher quality products and produces less waste because the prefabricated units are constructed in a controlled environment. This environment also leads to increased safety in comparison to on-site construction. For these reasons, this study explores the benefits of implementing prefabrication in the Mercy Health Muskegon project.

12.1 Modular Patient Room Private Bathrooms

Mercy Health Muskegon is a 267-bed hospital, which provides many opportunities for prefabrication. The existing design uses premanufactured head walls in the private patient rooms. Another opportunity for prefabrication is the bathrooms in the private patient rooms. There are 206 private patient bathrooms in the hospital, with an average of 30 per floor. A typical patient room plan and rendering are shown in Figures 84 and 85.

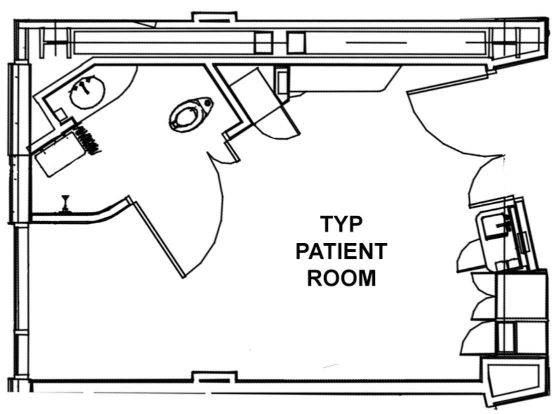


Figure 84: Typical Patient Room Bay

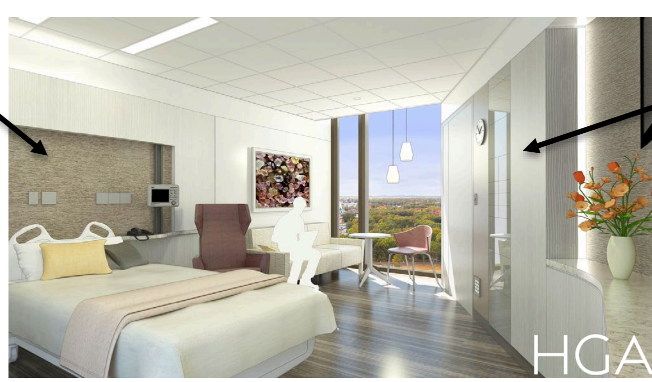


Figure 85: Patient Room Rendering

12.1.1 Cost and Construction Savings

A representative from Oldcastle SurePods, a factory-built bathroom provider in Orlando, FL, stated that healthcare projects with over 100 repetitive bathrooms could benefit from considering prefabricated bathroom pods. With 206 bathrooms and a stacked design with nearly identical floor plans, the repetitive elements make the Mercy Health Muskegon hospital an ideal candidate for prefabrication. The modular bathroom pods are composed of a concrete base and steel-framed, insulated gypsum and fibre panel walls. The pods contain all finishes and are fully equipped with piping for all plumbing and electrical systems. Many trades are involved in the construction of these bathrooms, so moving the construction off-site would reduce organizational conflicts between plumbing, mechanical, tiling, and other trades involved. The Modular Building Institute states that a dozen trades are required to install the 800 components in a typical hospital patient room bathroom over a three-month span. On the other hand, a bathroom pod can be installed in one day. Additionally, the Modular Building Institute estimates a 5.5% reduction in waste material than traditional construction site bathroom fabrication.

The Christ Hospital Joint and Spine Center in Cincinnati, OH utilized bathroom pods in their 87 private patient rooms (Whole Building Design Guide). The prefabricated pods resulted in an off-site construction cost of $2.8 million. Translating these numbers to the 206-bathroom Muskegon facility, the off-site construction costs would total approximately $6.6 million. Oldcastle SurePods estimates their healthcare pods to range from $30,000 to $35,000. The total cost would then fall between $6.2 million and $7.2, agreeing with the previous estimate.

RSMeans (Assemblies Costs 2018) estimates a typical bathroom to cost $6375. The material and installation costs would be $3775 and $2600 for each two-wall plumbing three fixture bathroom, containing a water closet, lavatory, and corner stall shower; however, these numbers are not project specific and do not directly correlate to a hospital bathroom, which is generally more costly due to the amount of specialized features and medical accessories required. This would result in a total cost of $1.3, which is significantly lower than the off-site construction cost. On the other hand, this would be offset by the considerable cost savings associated with a shorter construction schedule.

The Women's Hospital of Texas, a 100-bed hospital project that used bathroom pods, reduced its construction schedule by three months and gained $27 million in revenue based on an average revenue of $3000 per bed per day. Based on these numbers, the Mercy Health Muskegon construction schedule could be reduced by an estimated 6 months and earn an additional $144 million in revenue.

12.1.2 Logistics

Two healthcare case studies had 90 and 56 bathrooms pods installed over 22 and 14 days, respectively (The Modular Building Institute). This results in an average of 4 pods installed per day. The 206 bathrooms in the Mercy Health Muskegon bed tower would require approximately 52 days for pod installation. Oldcastle SurePods delivers and installs up to 30 units per day (Oldcastle SurePods). This would require only seven days of installation time and would be especially convenient for the theoretical Fort Lauderdale location since the provider is within a reasonable distance from the construction site. Oldcastle SurePods typically delivers five pods per truck, so this project would require 42 truck deliveries to the site.

Once the pods are delivered to the site, the installation process can begin. A proposed crane location for lifting the pods is shown in Figure 86. The existing structure prevents crane placement on that side of the addition. The proposed placement also allows all bed tower levels to be easily accessed without having to span across the D&T area.

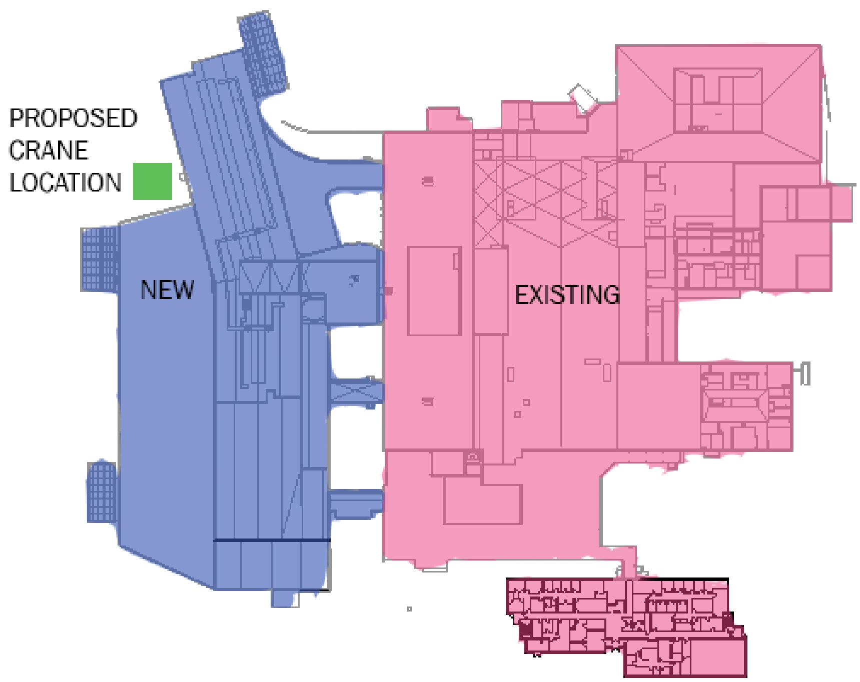


Figure 86: Proposed Crane Placement

A crane was specified based on the typical weight of a modular bathroom pod and the radius to a proposed drop-off area on a typical bed tower level. Sterchele Group, a bathroom manufacturer, states that the weight of a lightweight bathroom pod is one to three tons. A crane rental company based in Fort Lauderdale was referenced for crane technical data (Appendix A). The recommended crane is a Link-Belt Hydraulic Truck Crane (HTC) 86100. With a 140' main boom length and 35' fly length offset at 45° for a total radius of 65', the load capacity is 8,800 pounds or 4.4 tons. The reachable height is above the highest patient room floor height of 133'. The load capacity also exceeds the one to three-ton weight of a typical bathroom pod, so this crane is an acceptable choice.

After constructing the floor for a typical bed tower level, The Modular Building Institute states that mechanical and partition walls should be in place before the bathroom pods can be installed. Figure 87 shows the floor template and Figure 88 shows which walls would need to be framed with openings to accommodate the bathroom pods. Plumbing and mechanical rough-ins for these locations should also be completed at this time. The proposed crane and pod drop-off locations for a typical bed tower floor are shown in Figure 89. The drop-off location is directly near the crane location and in an area large enough to store several pods while others are being installed.

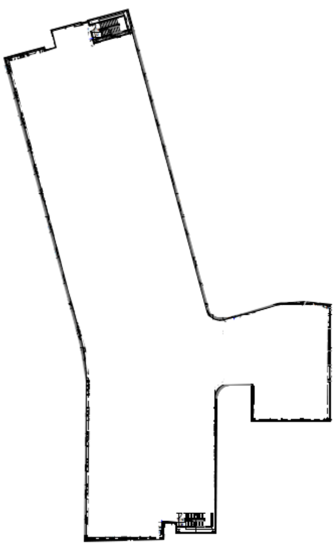


Figure 87: Bed Tower Floor Template

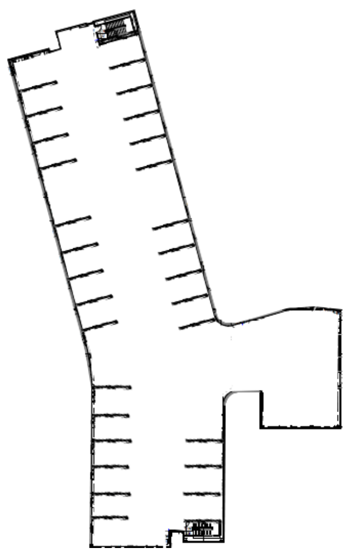


Figure 88: Wall Framing for Pod Installation

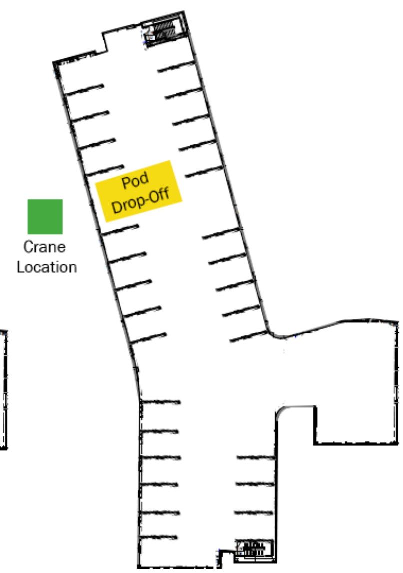


Figure 89: Crane and Pod Drop-Off Locations

Once the bathroom pods are hoisted, unloaded from the crane, and laid on the slab, they are rolled into place. It is important that the pathway to each pod's final location is clear, which is why the remainder of walls throughout the floor are left unframed at this stage. After proper alignment, simple connections can be made between the pod to the mechanical, plumbing, and electrical components. Figures 90 and 91 show the final pod locations and fully framed floor.

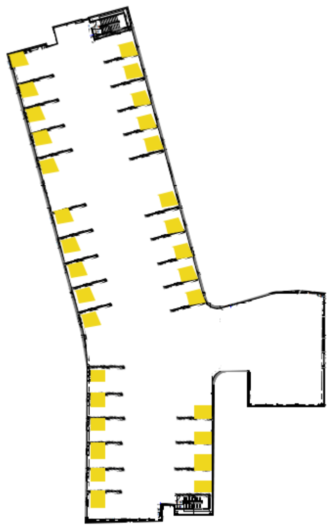


Figure 90: Final Bathroom Pod Locations

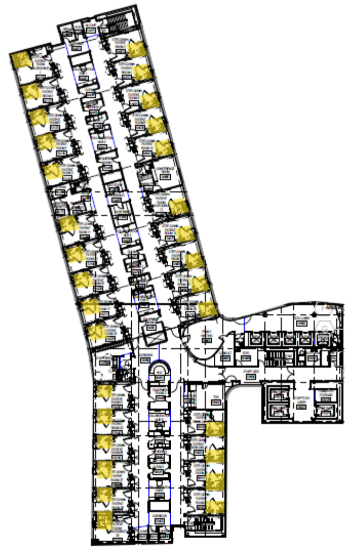


Figure 91: Completed Floor Plan

Two crews are required for the installation process. The first crew is required for crane operation and consists of one person operating the crane and two people directing the pod to its final position (StercheleGroup). Another crew of 3-4 people is needed to roll the pod into place and make connections to the MEP systems.

12.1.3 Prefabricated Bathroom Pod Summary

While significant planning, coordination, and design would be required at the beginning phases of the project, the use of prefabricated patient room private bathrooms would be very beneficial to the Mercy Health Muskegon medical center. A summary of the features of this implementation is provided in Table 19. Overall, prefabricated bathroom pods have a higher upfront cost but would provide better quality control, a safer construction site, less material waste, and a considerably shorter construction schedule.

Table 19: Prefabrication Comparisons

	On-site Construction	Prefabricated Bathroom Pods
Construction Duration	38 months	32 months
Construction Cost	$1.3 million	$6.6 million
Revenue Gained from Shorter Schedule		$144 million
Construction Material Waste	7%	1.5%
Crew Size		7 people
Equipment		Crane: Link-Belt HTC 86100
Installation Duration		7 days

13.0 Decision-Making Methods in the Structural Design of Healthcare Facilities

13.1 Decision-Making Methods in the Architecture, Engineering, and Construction Industry

In recent years the Architectural Engineering and Construction (AEC) Industry has evolved in many positive ways. This transformation includes new ideas and constraints on system selection, expanded methods of project delivery, condensed design and construction timelines, and multiple discipline considerations for system selection, to name a few (Tatum and Luth 2012). Part of this transformation involves the decision-making process for building design, which is not always straightforward. Decisions in the early phases of a project can have significant effects on the outcome, so it is important to weigh all options carefully (Mullur et al. 2003). New integrated practices where designs incorporate the best possible overall solution are becoming popular based on owner demands for efficiency and improved building performance. For design optimization, architectural and structural designer integration is beneficial in the early stages (Holzer et al. 2006). Through these early design phases, generating alternatives is very much iterative in that the content is not static but subject to continual change (Park and Holt 2010).

Conceptualization of building systems during design is perhaps the most important time for building selections as this determines the performance of the entire project. At this stage, interdisciplinary accommodations can be particularly challenging due to the occupancy types, complexity, and unique compositions of each project (Shen and Zhu 2011). The point in the lifecycle that is most "ripe" for meaningful performance impact is during conceptualization of the project solutions yet achieving this remains particularly challenging. The need for this study comes from the current challenges in the industry that impede design generation, including: 1) condensed timeframes, 2) increased building complexity, 3) competing and conflicting selection criteria, and 4) a lack of fast and simple multi-disciplinary design methodologies that permit the selection of the best overall solution.

When generating additional alternatives, there needs to be an effective way of selecting the best solutions. While there are many decision-making methods available, industry professionals often rely solely on knowledge and experience to make decisions; however, this opens up the potential to overlook better choices.

This literature review investigates the following Multi-Criteria Decision-Making (MCDM) methods: the Analytic Hierarchy Process (AHP), Choosing by Advantages (CBA), and the Pugh Matrix (PM). This research highlights the use of AHP, CBA, and PM primarily within the Architecture, Engineering, and Construction (AEC) industry. The majority of the literature reviewed was sourced from the ASCE journal database, with an emphasis on articles related to the decision-making process in the AEC industry. The goal is to outline the applications, benefits, and challenges of each method in order to study how the methods can be applied to structural design decision-making for healthcare facilities.

13.1.1 Creativity and Innovation

Engineering design is a field that demands innovation that can be reached only through a combination of creativity, intuition, and thoughtful choices (Toh and Miller 2016). While creativity is essential to generating innovative solutions, engineers often choose conventional or familiar designs to avoid risk; however, engineering design research has started to put an emphasis on creative idea development during the conceptual design and selection phases to promote innovation (Toh and Miller 2016). When designers choose previously successful design concepts without exploring alternatives, creativity is limited and can result in a solution that is not the best for meeting the unique goals of each project.

Designers who investigate more alternatives discover higher performing designs to these solutions. There is a dichotomy presented here: on the one hand, designers are urged to expand their thinking when making decisions, which can allow better performing solutions to emerge. On the other hand, they must make responsible decisions based on a limited number of metrics and available time in the early stages of design.

Historically, a designer created an efficient design that is safe by a) increasing the size of all the individual elements proportionally, b) trial and error, or c) approximate hand methods, all while largely focused on just their expertise area. This methodology approach provided some level of an optimized design but had limited interactions with other disciplines. Designers are now realizing that more robust designs are needed to satisfy owner requirements and the demand for high performance solutions across trades.

Introducing creative concepts into this process can be a complex task, but it can also bring about dynamic relationships than encourage further creative exchanges among stakeholders (Bowen et al. 2016). A willingness to discuss and accept creative ideas is critical. Due to bias against creativity, original ideas are often overlooked during the selection phase, so it is necessary to both introduce and adopt creative designs (Toh and Miller 2016). Formalized selection tools have been used to compare ideas, but they often fail to consider the importance of concept creativity (Toh and Miller 2016). As designers get more creative, they can benefit from selection tools that place an emphasis on creativity. Such tools could help promote or filter creative concepts leading to innovation throughout the design process (Toh and Miller 2016). Altogether, engineering design could benefit from the generation and selection of creative concepts that lead to innovative, high performance building solutions.

13.1.2 Decision-Making Background

The variety of project objectives and stakeholders across disciplines can complicate decisions within the AEC industry (Kpamma et al. 2016). While these decisions occur throughout the entire design and construction process, concept selection generally occurs during the conceptual design phase, which is often considered to determine 75% of the final project cost and quality (Mullur et al. 2003). Consequently, important decisions in the early stages of a project greatly affect the end results.

Several studies have found that industry professionals are using informal design approaches, such as intuitive selection, much more often than formal design techniques and decision-making methods (Frey et al. 2008). More often than not, design concepts are simply reused again and again. In light of rapidly evolving integrated teams and the sheer quantity of options generated, there is a need to develop processes and metrics for multi-criteria driven selection to achieve the best multi-disciplinary performance. To incorporate expert knowledge and experience, formal decision-making methods typically include substantial input from industry professionals through discussions, interviews, or surveys to establish the importance of decision-making criteria.

Several of these formal decision-making methods include the Analytic Hierarchy Process (AHP), Choosing by Advantages (CBA), and the Pugh Matrix (PM). While there are a variety of decision-making methods available, these three have been widely used across the AEC industry, engineering design disciplines, and many other fields. These approaches are useful for comparing multiple criteria and several design concepts, which is required when selecting the best building system for a project; therefore, they will be the focus of this research. AHP, CBA, and PM all require input from decision-makers for multi-criteria comparisons, but each method has advantages and disadvantages that lead to debate about their applicability and reliability.

13.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) *"structures a decision problem into a hierarchy of criteria, subcriteria, and alternatives, followed by a series of pair-wise comparisons to derive prioritized scales"* (Lam et al. 2007). This method is often chosen due to its ease of use (Wao 2017). Arroyo et al. (2015) states that applications of AHP are commonly found within the AEC industry and many other fields, which is likely due to its logical and mathematical appeal. AHP can be used in isolation to weight criteria and alternatives for system selection, and it has also been used along with other techniques; for example, the AHP weighting process has been used in combination with Fuzzy Logic (Bhatt et al. 2016) and Multi-Attribute Utility Theory (MAUT) (Doczy et al. 2017) approaches.

13.2.1 Using AHP

AHP uses the following procedure (Arroyo et al. 2015):

1. Establish a hierarchy consisting of a decision goal, criteria, subcriteria, and alternative concepts.

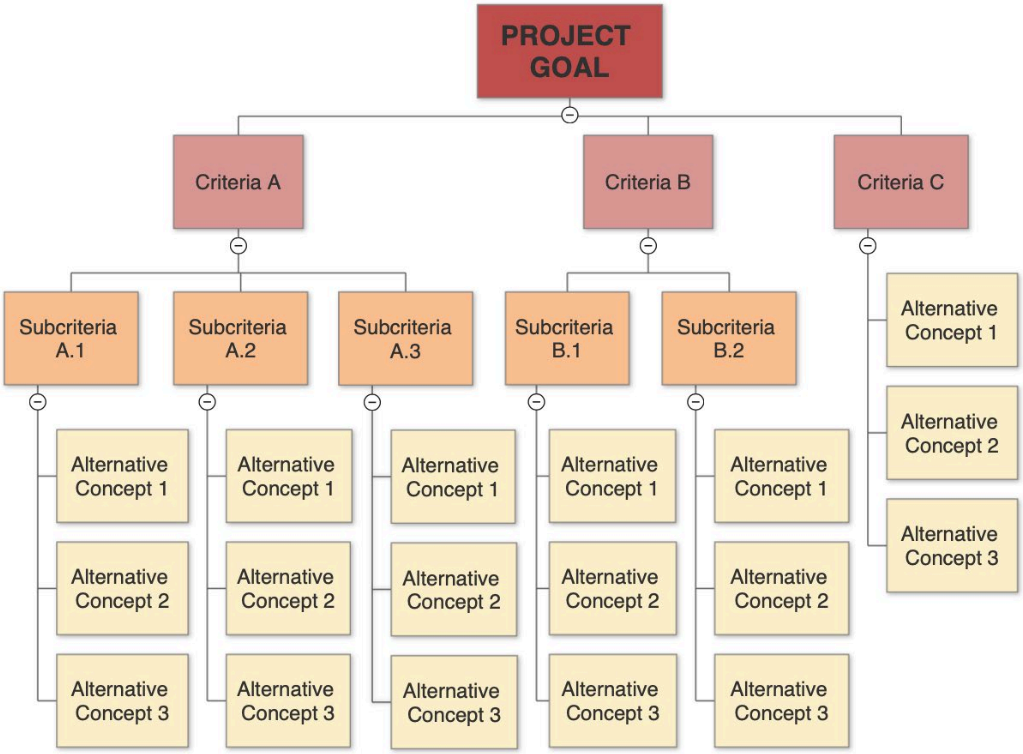


Figure 92: AHP Sample Hierarchy

Figure 92 displays a sample hierarchy with an overall project goal, three main criteria, several subcriteria, and three alternative concepts. Each criterion can have a different number of subcriteria or none at all. The alternative concepts at the lowest level are compared to the criteria or subcriteria directly above them in the hierarchy.

2. Weight factors through pairwise comparisons by assigning preference values as indicated in Table 20.

Table 20: Preference Values for AHP Pairwise Comparisons (Reproduced from Saaty et al. 2012)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Table 21 shows a sample pairwise comparison, using randomly assigned preference values, for the criteria. Comparisons between the same criteria always have a value of 1, indicating equal importance (McIntyre and Parfitt 1998). The first comparison between Criteria A and Criteria B has a value of 9, indicating that Criteria A has an extreme importance over Criteria B; additionally, the reciprocal of this value is entered into the cell for the comparison of Criteria B to Criteria A (McIntyre and Parfitt 1998).

Table 21: Sample AHP Pairwise Comparisons for Criteria

Criteria	Criteria A	Criteria B	Criteria C
Criteria A	1	9	3
Criteria B	1/9	1	1/4
Criteria C	1/3	4	1

Pairwise comparisons should also be performed for the subcriteria under each criterion. Finally, pairwise comparisons are performed for the alternatives with respect to each subcriterion or, for cases such as Criteria C with no subcriteria, the criterion above the alternative concepts in the hierarchy.

The pairwise comparisons in this step of the process are responsible for many of the challenges associated with AHP; comparisons between many criteria, subcriteria, and alternatives are time-consuming and complex (McIntyre and Parfitt 1998), tedious (Bhatt et al. 2012), and highly subjective (Doczy et al. 2017).

3. Determine the relative weights of factors "by calculating the eigenvalue vector of the preference matrix" (Arroyo et al. 2015).

The following calculation of relative weights follows a process summarized by Doczy and Abdelrazig (2017). The first step is normalizing the columns of the pairwise matrix, C, to form the matrix C_{norm} (Doczy and Abdelrazig 2017).

$$C = \begin{bmatrix} 1 & 9 & 3 \\ 1/9 & 1 & 1/4 \\ 1/3 & 4 & 1 \end{bmatrix}$$
$$\Sigma \quad 13/9 \quad 14 \quad 17/4$$

$$C_{norm} = \begin{bmatrix} \frac{1}{13/9} & \frac{9}{14} & \frac{3}{17/4} \\ \frac{1/9}{13/9} & \frac{1}{14} & \frac{1/4}{17/4} \\ \frac{1/3}{13/9} & \frac{4}{14} & \frac{1}{17/4} \end{bmatrix} = \begin{bmatrix} 0.692 & 0.643 & 0.706 \\ 0.077 & 0.071 & 0.059 \\ 0.231 & 0.286 & 0.235 \end{bmatrix}$$

The next step is calculating the eigenvector matrix by averaging the rows of the normalized matrix, C_{norm} (Doczy and Abdelrazig 2017).

$$W = \begin{bmatrix} \frac{0.692 + 0.643 + 0.706}{3} \\ \frac{0.077 + 0.071 + 0.059}{3} \\ \frac{0.231 + 0.286 + 0.235}{3} \end{bmatrix} = \begin{bmatrix} 0.680 \\ 0.069 \\ 0.251 \end{bmatrix} = \begin{bmatrix} = C_{Criteria\ A} \\ = C_{Criteria\ B} \\ = C_{Criteria\ C} \end{bmatrix}$$

The resulting matrix shows that the respective weights of Criteria A, B, and C are 0.680, 0.069, and 0.251. This process will be repeated for determining the weights of the subcriteria with respect to the criteria and the preferences of the alternative concepts with respect to the subcriteria.

4. Calculate the consistency index, also referred to as the consistency ratio. McIntyre and Parfitt (1998) state that a consistency ratio of 0.10 or less is acceptable for reaching the allowed 10% "margin of 'inconsistency."

The process for calculating the consistency ratio, as summarized by Mu and Pereyra-Rojas (2017), is shown below.

$$\mathrm{C} \times \mathrm{W} = \begin{bmatrix} 1 & 9 & 3 \\ 1/9 & 1 & 1/4 \\ 1/3 & 4 & 1 \end{bmatrix} \times \begin{bmatrix} 0.680 \\ 0.069 \\ 0.251 \end{bmatrix} = \begin{bmatrix} 2.054 \\ 0.207 \\ 0.754 \end{bmatrix}$$

$$\lambda_{max} = \frac{1}{n} \sum \frac{\mathrm{CW}_i}{\mathrm{W}_i} = \frac{1}{3} \sum \left(\frac{2.054}{0.680} + \frac{0.207}{0.069} + \frac{0.754}{0.251} \right) = 3.009$$

$$\mathrm{CR} = \frac{\lambda_{max} - n}{(n-1) \times \mathrm{RI}} = \frac{3.009 - 3}{(3-1) \times 0.52} = 0.009$$

Table 22 provides values for the average random consistency index, RI. In this example, the consistency ratio is less than 0.10, so no adjustments are needed.

Table 22: Average Random Consistency Index (RI) Values (Saaty and Vargas 2012)

N	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (R.I.)	0	0	0.52	0.089	1.11	1.25	1.35	1.40	1.45	1.49

5. Multiply factor weights by preference of alternatives. The alternative with the highest result is preferred. Table 23 (Saaty 2008) shows a layout of the preference calculation table for this process. The overall preference for each concept would be determined by summing the products of the corresponding criteria weights, subcriteria weights, and alternative concept weights.

Table 23: AHP Overall Preference Calculation Table Layout

Criteria	*Criteria A*			*Criteria B*		*Criteria C*	*Overall Prefer-ence*
Weight	--			--		--	
Subcriteria	*Subcriteria A.1*	*Subcriteria A.2*	*Subcriteria A.3*	*Subcriteria B.1*	*Subcriteria B.2*		
Weight	--	--	--	--	--		
Alternative Concept 1	--	--	--	--	--	--	______
Alternative Concept 2	--	--	--	--	--	--	______
Alternative Concept 3	--	--	--	--	--	--	______

13.2.2 Implementation of AHP

Table 24 lists a series of case studies that utilize AHP within the AEC industry. AHP can be applied to many decision-making scenarios and modified for various project types and locations. In addition to those listed in Table 24, other applications of AHP within the building industry include facility management, asset management, maintenance management, and demolition techniques (Lam et al. 2007). Variations of AHP have also been utilized for decisions within the AEC industry. Noorzai et al. (2017) applied the Analytic Network Process (ANP), which uses a network structure rather than a hierarchical structure, in a decision-making study for multifamily housing construction methods in Iran.

13.2.3 Advantages and Limitations of AHP

Many of the studies listed in Table 24 acknowledge the complexity and confusion that arise when there are a considerable number of criteria and pairwise comparisons. Since the decisions at this stage are subjective, inconsistencies in decision preferences are possible. The advantages of AHP here though include its ability to compare dissimilar elements and clarify design preferences. Another advantage is flexibility. While the simplicity of AHP makes it a popular method, inconsistency in AHP judgments and dependent relationships between decision elements are a concern (Noorzai et al. 2017).

Though widely used, AHP is not suited for every situation. Attallah et al. (2017) conducted a study of LEED credit selection and determined that the ELECTRE III method was preferred over AHP because of its ability to analyze quantitative and qualitative criteria without converting the criteria to a single scale. This shows that the numerical scales used in AHP may be considered an advantage or a disadvantage based on the situation. Wao (2017) also states that AHP may be limited for reaching sustainability goals because it relies on abstract comparisons and criteria weights while also possibly introducing the issue of double counting.

Table 24: Analytical Hierarchy Process Research Summary

	Case Study Info			*Decision Method Analysis*		
Category	Case Study Topic	Project Type	Project Location	Advantages	Disadvantages	Source
Planning (Residential Land Development Site Selection)	Selecting the best of three existing sites for a proposed residential development	Residential subdivision with 50-60 single-family detached houses	Ferguson Township, PA	Consistency ratio takes into account evaluation inconsistencies Can be modified and used for other sites and areas of the residential land development process	May have considerable pairwise comparisons for complex problems, requiring an application tool for computations Must determine user and system responsibilities	McIntyre and Parfitt 1998
Design	Determining preferences for three suicide barrier design solutions	Golden Gate Bridge suicide barrier	San Francisco, CA	Useful for clarifying importance of values Outlining preferences can help the group decision-making process	Inconsistencies in decision preferences No quantification of uncertainty May not be best suited for specific design recommendations	Hutchings et al. 2007
Construction (Constructability)	Evaluating building construct-ability based on individual superstructure construction systems (frames, slabs, envelopes, etc.)	Buildings with commonly adopted construction systems in Hong Kong	Hong Kong, China	Procedure can be replicated to other locations using relevant construction systems Provides numerical scales that quantify relative constructability performances	Not defined	Lam et al. 2007
Construction (Lean Construction)	Assessing the success of a lean construction plan	Combined cycle power plant	Damavand, Iran	Not defined	Not defined	Heravi et al. 2018

	Case Study Info			*Decision Method Analysis*		
Category	Case Study Topic	Project Type	Project Location	Advantages	Disadvantages	Source
Sustainability	Developing parameter global weights for assessing sustainable buildings in India	Not specified	India	Useful and reliable for comparing independent criteria and both qualitative and quantitative issues Widely recognized, effective, and logical process	Tedious when many alternatives or criteria are involved Lengthy surveys often result in low consultant response rates	Bhatt et al. 2012
Sustainability	Assessing the sustainability performance of commercial buildings with a combined AHP and Fuzzy Logic approach	Commercial buildings	India	Ease of use Criteria weights allow consistent comparisons of dissimilar elements Scalability	Not defined	Bhatt et al. 2016
Sustainability and Costs	Selecting a new construction design considering net-zero, LEED, and cost goals with a combined AHP and MAUT approach	(1) Eastside Branch Library (2) FAMU-FSU College of Engineering	Tallahassee, FL	Criteria weights allow comparisons of dissimilar elements Project elements can be prioritized	Difficult to validate results due to the subjectivity involved in pairwise comparisons	Doczy et al. 2017

13.3 Choosing by Advantages (CBA)

Choosing by Advantages (CBA) is a decision-making method that compares advantages of alternative design concepts. In comparison to AHP, CBA has not been as widely studied and used in the AEC industry (Arroyo et al. 2015). CBA is commonly applied to decisions involving lean construction (Arroyo et al. 2015). It has proven to be an effective tool for construction-related decisions, some of which include sustainable designs, safety measures, and material choices which could make it a candidate for system design (Karakhan et al. 2018).

13.3.1 Using CBA

CBA can be implemented by following these steps (Arroyo et al. 2015):

1. Summarize the qualities or characteristics, known as attributes in CBA, of each alternative in reference to a set of chosen factors and criteria.

Arroyo et al. (2015) defines a factor as *"an element, part, or component of a decision."* A criterion is defined as *"a decision rule or a guideline"* and can be either a desirable or mandatory rule (Arroyo et al. 2015). For example, structural gravity system comparisons may include factors such as structural depth, weight, and vibration performance. The respective criteria for these factors may be that a lower structural depth and weight are desired but the system must meet specific vibration performance requirements that fall below a certain acceleration limit. The attributes of each structural system would then specify depth of the floor and framing, weight, and vibration performance.

2. Determine the advantages of each alternative.

An example of an advantage for a structural system may be that it has 50% less weight than an alternative system, and the alternative system with a higher weight would not have any advantage for this factor. Arroyo et al. (2015) states that factors have no importance when an there is no advantage between the alternatives; therefore, it is not required to remove these nondifferentiating factors, as the equal performance of the alternatives will not affect the results.

3. Determine the most important advantage and assign it a score, which is then used as a reference point to assign Importance of Advantage (IoA) scores to the remaining advantages. This is a subjective process where the stakeholders determine the most important advantage, assign it a score, and use that as a reference point for assigning scores to the remaining advantages.

4. Calculate the sum of the IoA scores for each alternative. A higher score represents a more advantageous concept. Table 25 shows a layout of steps 1-4 for a sample CBA comparison.

Table 25: Sample Layout for SBA Steps 1-4

		Alternative 1			*Alternative 2*		
Factor	Criteria	Attributes	Advantages	IoA	Attributes	Advantages	IoA
Structural Depth	Lower is better	24”	33% less depth	100	36”	--	--
Structural Weight	Lower is better	80 k	--	--	40 k	50% less weight	50
Vibration Performance	Under 0.5% g, lower is better	0.217% g	48% better acceleration performance	30	0.421% g	--	--
Total	--	--	--	130	--	--	50

If the alternative with the highest sum of IoA scores also has the lowest cost, this consideration is unnecessary. When this is not the case, a plot of the total IoA scores versus the estimated cost for each alternative can be used to make this comparison, but it must ultimately be decided whether more advantages justify the additional cost (Kpamma et al. 2016). Figure 2 displays a sample comparison for Alternative 1, which has a higher total IoA and cost, and Alternative 2, which has a lower total IoA and cost. It is important to consider value for money, and some questions to ask during this stage include how important are factors such as life-cycle cost, relationship between a chosen alternative and other building systems, and trade-offs that may be required across other disciplines (Arroyo et al. 2015).

13.3.2 Implementation of CBA

Table 26 summarizes numerous case study applications of CBA within the AEC industry. This method has been successfully used for design, construction, and sustainability decisions. There is an assortment of case study project types and locations, each of which has its own unique set of criteria and requirements.

13.3.3 Advantages and Limitations of CBA

One advantage of CBA is that is can be easily adapted to different projects. Another commonly referenced advantage of CBA is that it avoids double counting by focusing on the importance of advantages, unlike AHP comparisons of advantages to disadvantages (Kpamma et al. 2016). On the other hand, it may be difficult for stakeholders to reach agreements on the attributes and advantages of each alternative, which can result in a lengthy decision process. Since CBA has not been used as extensively as other MCDM methods, greater time and effort may be required on top of what is already a highly detailed and demanding process early in the project.

Table 26: Choosing by Advantages Research Summary

	Case Study Info			*Decision Method Analysis*		
Category	Case Study Topic	Project Type	Project Location	Advantages	Disadvantages	Source
Design	Choosing between two sustainable insulation materials	Sample project: six-story building	Northern California	Avoids double-counting factors Minimizes conflict among stakeholders		Arroyo et al. 2012
				Highlights advantages which makes it easy to understand tradeoffs Nondifferentiating factors do not affect the outcome Objective tasks come before subjective tasks	No guidelines for managing interrelated factors Difficult to apply during conceptual design when attributes are not clear	Arroyo et al. 2015
Design	Choosing a sustainable ceiling tile material	Commercial office buildings	Considers office locations in San Francisco, New York, Sydney, Dublin, and Tokyo	Transparent and collaborative environment Broader analysis of alternatives in comparison to the LEED rating system	Data collection and analysis may be too time consuming Difficult to gather all stakeholders for discussions	Arroyo et al. 2016
Design	Choosing between two conceptual designs for a building expansion	Operating theater building at the Holy Family Hospital	Techiman, Ghana	Simple, explicit, and transparent Promotes user involvement and collaboration Clearly outlines advantages which encourages stakeholders to consider design alternatives	Describing and agreeing on attributes may require significant time and effort	Kpamma et al. 2016

	Case Study Info			*Decision Method Analysis*		
Category	Case Study Topic	Project Type	Project Location	Advantages	Disadvantages	Source
Design	Identifying the best of 11 fall protection system alternatives	Bridges (maintenance worker protection)	United States, District of Columbia, Puerto Rico	Recognized as a collaborative, transparent, and reliable tool	Not defined	Zuluaga et al. 2018
Construction (Formwork Selection)	Selecting a formwork system for a large affordable housing development	700 single-family units in an affordable housing development	Duran, Ecuador	Promotes social interaction and collaborative discussions between decision makers Adaptable to the uniqueness of projects	Note defined	Martinex et al. 2016
Construction (Bidder Selection)	Selecting one of three bidders for the construction of an academic office building	Mission Hall (academic office building) at the University of California, San Francisco	San Francisco, CA	Earlier application can help owners define project requirements and goals Considers cost and value separately	Requires a high level of detail and more effort early in the project	Schöttle et al. 2017
Construction (Contractor selection)	Evaluating contractor safety maturity for the purpose of awarding a construction contract	Three-story building for the Oregon State University	Corvallis, OR	Placing subjective decisions last expedites the decision-making process Creates a transparent and collaborative environment	Learning how to apply CBA requires significant time and effort during early stages of a project Not applicable to all situations	Karakhan et al. 2018
Construction and Sustainability	Evaluating the value engineering process for building sustainability	Sustainable building in construction	Florida	Approach addresses shortcoming in the traditional VE method	Requires continued learning	Wao 2017

13.4 Pugh Matrix (PM)

Of the three methods discussed in this research, the Pugh Matrix (PM) is the simplest decision-making technique. Due to its simplicity and lack of complex mathematical procedures, this method is widely recognized (Burgren et al. 2015); however, its use for decision-making in engineering practices may be less common. One study indicated that only 15% of the 106 surveyed practicing engineers had used this method and found it useful, while another survey found that approximately only 2% of firms use this approach (Frey et al. 2008). While the PM is a simple method, it may be overlooked in favor of experience-based decisions that do not apply a structured decision-making method (Frey et al. 2008).

13.4.1 Using PM

As outlined by Thakker et al. (2009), the steps of the PM analysis are as follows:

1. Choose evaluation criteria.

2. Create the decision matrix. The criteria are entered in the rows and the alternative concepts are entered in the columns.

3. Select a baseline concept that the alternative concepts will be compared to. This is often a well-known concept or one that has been proven to have good performance, such as an industry leader, for the application being considered (Frey et al. 2008).

4. Complete the matrix by comparing the alternative concepts with the baseline, or datum, concept. Comparison scales use the following three levels to indicate that an alternative is better than (+ or 1), the same as (S or 0), or worse than (- or -1) the baseline. The baseline will have ratings of all S or 0 since it cannot be better or worse than itself.

5. Determine the total ratings assigned to each concept by summing the scores.

It is important to note that many applications of PM utilize criteria weights, as well. The scores would be multiplied by the criteria weight and then summed to provide a weighted rating. There are several ways to calculate criteria weighs for use in PM analysis. Interviews, surveys, and MCDM methods such as AHP and ANP are several tools that can be used to generate criteria weights (Nixon et al. 2013). Additionally, stakeholders or team members can individually assign weights to the criteria, which can then be averaged for final weights (Burgren and Thoren 2015).

6. Based on the total ratings, determine which concepts should be removed from consideration and which should be pursued further.

7. Continue to evaluate the remaining concepts by following the same procedure. The baseline for each new trial should be the highest rated concept from the previous analysis.

A sample Pugh matrix is shown in Table 27. In this example, Alternative 2 has the lowest total rating so it would be discarded. Alternative 3 has the highest total score so it would be the baseline in a proceeding comparison with Alternative 2. The alternative with the highest rating after this analysis would be considered the best option.

Table 27: Choosing by Advantages Research Summary

		Concepts			
Criteria	Weight	*Baseline*	*Alternative 1*	*Alternative 2*	*Alternative 3*
Criteria A	5	0	1	0	1
Criteria B	2	0	1	0	-1
Criteria C	3	0	-1	1	1
	Total	0	4	3	6

13.4.2 Implementation of PM

Table 28 lists several PM engineering case studies implementing PM. It also includes a list of the advantages and disadvantages based on the case studies and general research of the PM as a decision-making method. Since the PM is frequently found throughout mechanical design literature (Takezawa et al. 2005), many of the included case studies relate to the mechanical engineering field. Additionally, the case study by Ha et al. (2016) uses PM as a part of Six-Sigma. Despite its complexity, Six-Sigma management often uses the uncomplicated PM as a tool (Alemam et al. 2016).

13.4.3 Advantages and Limitations of PM

As summarized in Table 28, the simple structure of the PM can be applied to a wide variety of decisions, but it introduces several benefits and challenges. Although this method is simple and saves time, it relies on subjective decisions that can produce bias and inconsistencies.

Table 28: Pugh Matrix Research Summary

	Case Study Info			*Decision Method Analysis*		
Category	Case Study Topic	Project Type	Project Location	Advantages	Disadvantages	Source
Design	Selecting one of three novel solar thermal collector concepts	Novel solar thermal collector	Gujarat, India	Simple and quick selection method	Not defined	Nixon et al. 2013
Design (Structural Component)	Developing and effective steel beam section for use in modular construction	Modular construction	Not specified	Not defined	Not defined	Ha et al. 2016
Design (Mechanical Product)	Evaluating alternative designs to optimize the design of an impulse turbine	Impulse turbine	Not specified	Effective for comparing less refined designs Facilitates product design and selection	Not defined	Thakker et al. 2009
Design (Mechanical Product)	Selecting an eco-design hair-dryer	Hair-dryer	N/A	Simple and well-recognized matrix format	Not defined	Alemam et al. 2016
Design (Mechanical Product)	Selecting the automotive HVAC TXV	Automotive HVAC system development	Not specified	Easy to understand which concept has more focus to fulfill needs	Not defined	Sambandan et al. 2018
Energy	Choosing an alternative use for excess heat	Heat and electricity production company	Sweden	Simple and time saving Promotes group communication and decision-making	Judgments are subjective and influenced by user bias No software implementation	Burgren and Thoren 2015
None	None	None	None	Avoids the misleading nature of weights	Does not describe relationships between criteria	Mullur et al. 2003
None	None	None	None	Easily interpreted visual format	May lead to inconsistencies or distortions in the decision-making process	Frey et al. 2008

13.5 Multi-Criteria Decision-Making Method Comparisons and Summary

13.5.1 Comparison of AHP, CBA, and PM

Table 29 provides a summary of the common uses, advantages, and disadvantages associated with AHP, CBA, and PM. The PM uses weighted criteria and a +1, 0, and -1 scoring scale to compare alternatives against a reference alternative. This is the simplest method, but it has not been well documented in AEC literature. It has proven to be a timesaving procedure for its many mechanical applications, but it may be oversimplified, as it does not contain much information to describe relationships between criteria. The AHP is a more detailed procedure that has been frequently documented inside and outside the AEC industry. This method uses a more specific scale of 1-9 for pairwise comparisons to weight a hierarchy of criteria, subcriteria, and alternatives. Pairwise comparisons are subjective and complicated when many criteria are being compared. AHP is often preferred for its mathematic appeal and numerical scale that allows diverse elements to be compared. While AHP risks double counting, CBA compares only advantages to avoid this issue. CBA compares beneficial attributes of alternatives to determine which alternative has the most favorable advantages. Often used in construction-related decisions, this method promotes transparency and collaboration, but it may require more time and effort at early stages of a project.

13.5.2 Lifecycle Phase for Deploying MCDM Methods

Current lifecycle processes within the AEC industry still largely cling to the traditional means, methods, and best practices. Companies are still, to some extent, operating in isolated silos, particularly outside of multidisciplinary firms (Middlebrooks and Hammond 2010). Perhaps the most beneficial time in a project's lifecycle for deploying MCDM methods is early in design when the critical design decisions are made (Solnosky 2013 and Schumacher and Otani 2012).

Conceptualization Design is a challenging point of the design process as it requires reconciling the design with complex goals and constraints (Gane and Haymaker 2007). Before conceptualization, several key aspects that support the critical tasks within this design phase need documented by the project team. The first is the development of initial project drivers (e.g. cost, quality, sustainability, and system efficiency, for example) and their associated priorities. Following these, the primary structural design criteria (e.g. objectives, requirements, boundaries, and performance, for example) are postulated. Defining these aspects allows for a standard basis to compare the subsequent designs. These criteria often differ based on project type and current industry trends.

Table 29: AHP. CBA, and PM Comparisons

Decision-Making Method	Most Common Uses	Advantages	Disadvantages
Analytical Hierarchy Process (AHP)	Construction Sustainability	Weighted criteria allows comparison of dissimilar elements Numerical scales quantify preferences and performances	Subjectivity can lead to inconsistencies in decision preferences Tedious and complex when many pairwise comparisons and lengthy surveys are involved
Choosing by Advantages (CBA)	Design Sustainable material selection (Lean) Construction	Transparent and collaborative Comparisons advantages makes tradeoffs easy to understand and avoids double-counting Subjective decisions are made at the end of the decision-making process, which reduces bias and expedites the process	Requires significant time, effort, and detail early in the project Can be difficult to gather all stakeholders and reach agreements for project goal importance and alternative design attributes
Pugh Matrix (PM)	Mechanical design	Simple and time saving Well-recognized matrix format	Can be used to compare less refined designs Based on subjective decisions that can introduce bias and inconsistencies

13.5.3 Healthcare Design Overview

Healthcare designs are constantly evolving and becoming more competitive, pressuring designers to reduce costs while accelerating the design and construction schedules and meeting the highest quality standards (Carr 2017). This is not a simple task, so many healthcare professionals have devoted their time to pursuing ways to create better and more efficient designs (Fabris 2014). These designs are typically driven by patient experience and future flexibility (Kovacs Silvis 2018). The demand for design flexibility is fueled by the healthcare market's need to renovate, modernize, and expand (Kovacs Silvis 2018). Prefabricated parts and units are also becoming more widely used to meet schedule and safety demands (Fabris 2014). With many factors and goals to consider, guiding design towards efficiency is critical. Some healthcare teams have analyzed process flow with mapping and simulation tools to guide design that is informed by visioning and modeling (Fabris 2014). Concentrating on project goals and striving for design efficiency is imperative for healthcare designs in today's market and leads to informed decision-making.

13.5.4 Research Summary of Decision-Making in the AEC Industry

Many MCDM methods have been studied and applied to various design and engineering projects. AHP, CBA, and PM have been researched and used individually for a variety of decision-making situations; however, there are few studies that directly compare the methods. The majority of AEC decision-making case studies have focused on decisions related to construction and sustainability. There is little documentation related to building design, especially structural designs. One limitation of this research is that the use of these methods is not always documented. Based on this literature review, there is a gap in knowledge for the decision-making process for structural system selection in building designs. It will be useful to compare the applications of AHP, CBA, and PM to the selection of a case study structural system, paying close attention to the downfalls of each method and how they can best be avoided. These results will be used to determine the applicability of each method to both general structural decisions but more specifically related to healthcare facilities.

13.6 Decision-Making Methods for Healthcare Facilities Survey

A survey about decision-making methods for healthcare facilities was sent to professionals in the AEC industry, specifically those within firms that have extensive healthcare project portfolios. The goal of the survey was to collect information about how industry professionals select systems in healthcare projects. While the objective is to analyze the criteria that most strongly and frequently affect structural system selection, input is desired from professionals with experience across all building disciplines. This will provide insight into how each expertise interacts with structural systems in healthcare projects. The full survey can be found in Appendix B.

The survey received 38 responses. Of these, 27 were complete or mostly complete responses, and 11 were partial responses. The participants have an average of 21.6 years of building industry experience. The most commonly reported licensures were P.E. (25) and LEED A.P. (17). The discipline breakdown of the participants is shown in Figure 93. Most survey responses were from the structural discipline. Numerous other disciplines are also represented, which will provide valuable feedback about how non-structural disciplines consider the impact of structure systems within healthcare facilities. Project experience for all participants extends to a wide variety of healthcare projects, such as traditional patient, ICU, and surgical facilities to name a few. Furthermore, most of the respondents had worked in all or almost all phases of design from early planning to construction administration.

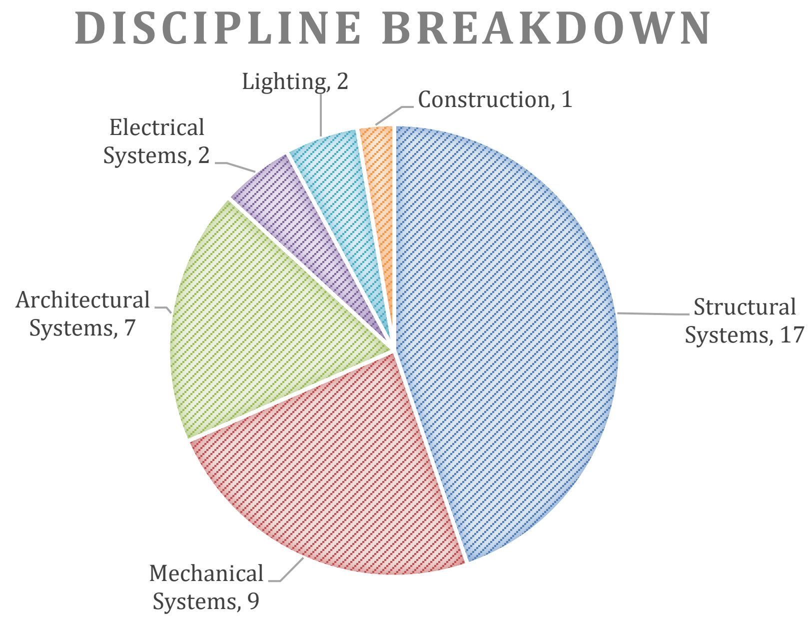


Figure 93: Survey Respondent Discipline Summary

The responses show that broad system conceptualization occurs primarily during the conceptual design and schematic design phases. A full rundown of the broad system conceptualization phases is displayed in Figure 94. The general consensus is that, early on, rule of thumb is typically use in lieu of detailed mathematical calculations for decisions at these phases. As the design progresses, or when projects are more complex, the designs become more detailed for individual bays. The responses show that the design of these broad systems is typically narrowed down to a single design in the schematic design phase. Figure 95 summarizes the responses for when narrowing of designs occurs. The respondents generally agreed that the owner is responsible for the final decision with input from the design team (architects, engineers, etc.) and contractor/CM. Notably, this decision is heavily influenced by cost.

Cost and schedule are the main factors affecting which systems are selected to move forward with or are discarded. Cost-value analyses are also used to look at factors such as future, flexibility, vibration performance, life span, existing conditions, and project location/constructability. To aid with decisions involving these factors, the participants reported use of the following decision-making methodologies:

- (13) CBA
- (12) Ranking
- (7) Majority vote across all project team members
- (3) Set-based design
- (2) Majority vote inside discipline

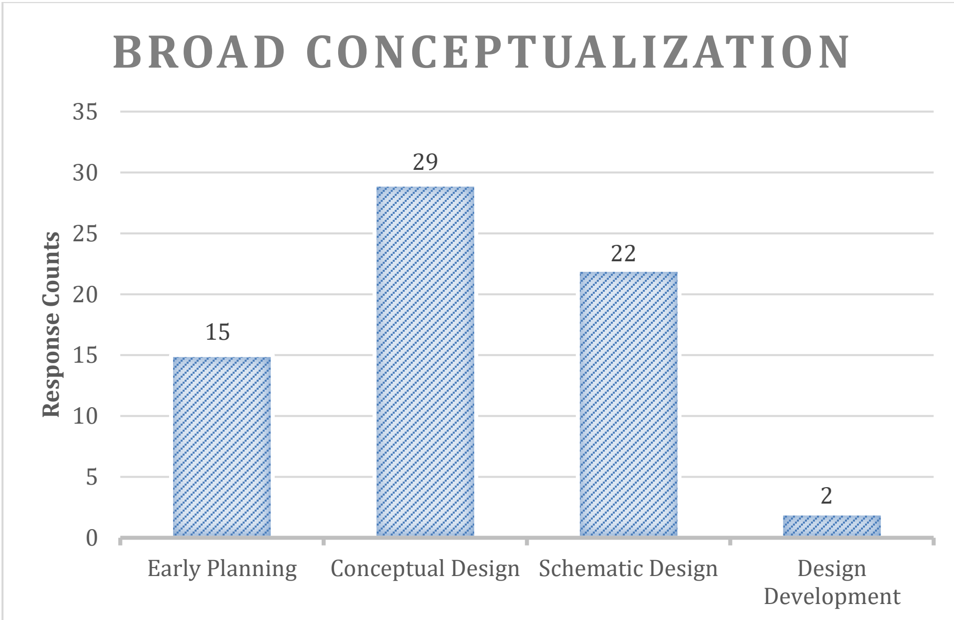


Figure 94: Phases for Broad System Conceptualization

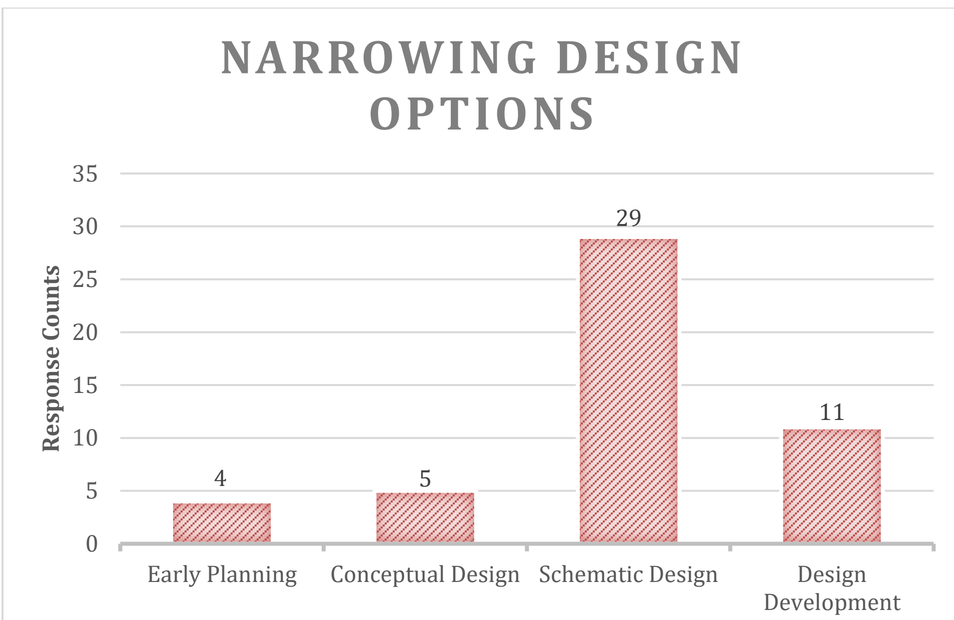


Figure 95: Phases for Narrowing Design Options

CBA was the most popular choice, but no participants used AHP or PM; however, the majority of the participants said they would or maybe would use any of these decision-making methods if they were easy to use or would provide a benefit to the project.

The decision-making process typically incorporates parameters based on the project goals, owner preferences, contractor input, cost, schedule, flexibility, and architectural plans. The categories of parameters included in the survey include healthcare, general, architectural, construction, and structural. The participants were asked how often they consider specific parameters within each broad parameter category. Then they were asked how important each specific parameter is on a scale of 0 to 100. The parameters were ranked based on the mean of these importance rankings. The mean was also verified with geometric and harmonic means to determine if the data was significantly skewed or contained outliers.

The most commonly considered healthcare parameters are patient security and safety; special materials, finishes and details for spaces which are to be kept sterile; designing for operation and maintenance (O&M) practices; planned directions for future expansion; and providing optimal functional adjacencies. The order of importance is as follows:

1. Planned directions for future expansion
2. Patient security and safety
3. Following modular concepts of space planning and layout
4. Providing optimal functional adjacencies
5. Repetitive room sizes and plans
6. Designing for O&M practices
7. Special materials, finishes, and details for spaces which are to be kept sterile
8. Providing views of the outdoors
9. Travel routes
10. Homelike and intimate scale in patient rooms
11. Increased use of natural light

The most commonly considered general parameters are system cost, future flexibility, and future renovations. The following list shows the order of importance for the general parameters:

1. System cost
2. Future flexibility of the space
3. Future renovations
4. Sustainability (rating system(s) scores)
5. Sustainability (embodied carbon and emissions)

The most commonly considered architectural parameters are maximizing floor-to-ceiling height, plenum coordination, minimizing floor-to-floor height, number of floors/stories, and plenum depth. The architectural parameter order of importance is as follows:

1. Maximizing floor-to-ceiling height
2. Plenum coordination
3. Plenum depth
4. Number of floors/stories
5. Minimizing floor-to-floor height
6. Maximizing net floor area
7. Gross floor area
8. Embracing architecture irregularity
9. Movability of the architecture

The most commonly considered construction-focused parameters are minimizing size impact, enhancing or easing erection/construction time, and repetitive members. The majority of respondents also considered offsite prefabrication ability very often. The following list shows the order of importance for the construction-focused parameters:

1. Minimizing size impact
2. Enhancing/easing erection/construction time
3. Repetitive members
4. Offsite prefabrication ability

The most commonly considered structural-focused parameters are structural member/system weight and following system layout parameters: optimizing orientation of the system, minimizing number of members, maximizing spacing/dimensions. The structural-focused parameter order of importance is as follows:

1. Structural member/system weight
2. Layout of the system (maximizing spacing/dimensions)
3. Layout of the system (optimizing orientation of the system)
4. Minimizing structural depth
5. Fire resistance
6. Layout of the system (minimizing number of members)
7. Having a good bay aspect ratio for the system of choice

Of these parameters, the healthcare parameters were reported to vary the most among different types of healthcare projects, followed by structural-focused, architectural, construction-focused, and general condition parameters. Average importance values assigned to each of these parameters, not including healthcare, can be found in Section 13.7.2.

In summary, the survey results show that many structural system decisions are made in the early phases of a project, specifically the conceptual design and schematic phases. These become more refined at the schematic design phase where designs are eliminated until a single option remains. The rule of thumb assessments used during conceptualization becomes more detailed as the design progresses. The decisions used throughout this process depend on a wide variety of criteria. To narrow down alternative systems based on these criteria, the respondents use decision-making methods such as CBA and ranking. The industry professionals show a willingness to use other formal decision-making methods, such as AHP and PM, if they were proven to be simple and beneficial.

13.7 Gravity System Decision-Making Application

13.7.1 Criteria Selection

Based on the decision-making survey results, parameters that are mostly frequently considered for structural system selection were potential criteria for the gravity system decision-making case study. Of these, only the parameters that are applicable to the Mercy Health Muskegon gravity system selection case study are used for the decision-making criteria. The criteria categories are the same as the overall parameter categories. These include general (G), architecture (A), construction (C), and structural (S). The specific criteria or subcriteria for each category, and the corresponding labels used to denote them in the AHP, CBA, and PM analyses, are summarized in Table 30.

Table 30: Criteria and Labels

Criteria / Factor	AHP and PM	CBA
Sustainability (carbon emissions)	G1	F1
Future flexibility of the space	G2	F2
System cost	G3	N/A
Plenum depth	A1	F3
Plenum coordination	A2	F4
Repetitive members	C1	F5
Enhancing/easing erection/construction time	C2	F6
Layout of the system (minimizing number of members)	S1	F7
Structural member/system weight	S2	F8
Minimizing structural depth	S3	F9

13.7.2 Criteria Weighting

The decision-making survey asked industry professionals to assign parameters, or subcriteria, an importance value on a scale of 0 to 100, with 0 = no importance/not influential and 100 = utmost importance/hugely influential. Since these allow a lot of room for interpretation of intermediate values, it is difficult to correlate the scores from person to person. To avoid large discrepancies, a binned ordinal transform was used to rank the subcriteria in order of importance. A binned ordinal transform ranks the scores based on importance, but scores that are close in value are binned together and are assigned the same rank. For example, scores of 50, 10, 80, and 85 would be ranked 2, 1, 3, and 3. The higher ranks indicate a higher level of importance. This process was used for the subcriteria within each criteria category. Only responses that assigned scores to all or almost all of the subcriteria were considered. If only one subcriterion was not assigned an importance score, it was assumed to have the lowest rank.

The ranks for each subcriterion were summed. The sums for each subcriterion within their corresponding criteria category were then added together. Subcriteria weights were determined by dividing the total subcriterion rank by the sum of the total subcriteria weights for each criteria category. Weights were also determined for the criteria categories using the same process; however, in this case the average of all the subcriteria importance scores in each category were used for ranking. Combined weights for the subcriteria were then calculated by multiplying the subcriteria weight by the criteria weight. Sample calculations for the criteria weights and combined weights are shown in Tables 31 and 32.

Table 31: Criteria Weighting

Criteria	Average Survey Score for All Subcriteria within Parameter Category	Ranking, R (higher rank preferred)	Weight = $R_i/\Sigma R$
General	74.6	1	0.1
Architectural	78.7	4	0.4
Construction	77.7	2	0.2
Structural	78.3	3	0.3
	ΣR	10	

Table 32: Combined Weights

Criteria	Subcriteria / Factor	Weights		Combined Weight = Criteria Weight x Subcriteria Weight
		Criteria	Subcriteria	
General	G1 / F1	0.1	0.22	0.022
	G2 / F2		0.37	0.037
	G3		0.41	0.041
Architectural	A1 / F3	0.4	0.50	0.200
	A2 / F4		0.50	0.200
Construction	C1 / F5	0.2	0.49	0.098
	C2 / F6		0.51	0.102
Structural	S1 / F7	0.3	0.32	0.096
	S2 / F8		0.35	0.105
	S3 / F9		0.33	0.099

The highest weighted and most important criteria are plenum depth and coordination followed by structural weight and enhancing/easing erection/construction time. The lowest is sustainability.

Since CBA does not typically use cost as a factor for comparisons, cost was excluded from weighting process and the weights were recalculated. This has an effect on only the general criteria category. Since CBA is based on IoA scores instead of weights, an additional step was needed. As shown in Table 33, the factors are ranked based on the combined parameter weights determined from the survey results, with lower ranks indicating a more preferable ranking and higher importance. Each factor is then assigned a category importance based on intervals of 25. The factor with the lowest combined weight, and therefore the worst ranking, receives the lowest category importance of 25. Since two subcriteria have the same combined weight, they are assigned the same importance. Though the category importance values area based on intervals of 25, this scale is arbitrary and does not affect the outcome. Only the relative importance values between the criteria have meaning. The category importance values indicate the maximum IoA that a system and its attribute can receive for that factor. In the CBA analysis, each attribute is assigned an advantage in comparison to the least preferred attribute. The attributes are then assigned an IoA, with the lowest ranked attribute receiving a 0 IoA and the highest ranked attribute receiving an IoA equal to that of the factor's category importance. Attributes with intermediate rankings are assigned an IoA that is proportional to its advantage and the category importance range.

Table 33: CBA Factors, Criteria, Attributes, and Importance

Factor	Criteria	Attribute and Unit	Combined Weight Based on Survey Results (excluding cost as a subcriteria)	Ranking	Category Importance
F1	Lower is better	Carbon content (kg CO_2)	0.037	8	25
F2	Lower number of members and lower utilization ratios are better	Total number of members, Average demand to capacity ratio	0.063	7	50
F3	Lower depth is better	Beam depth (in)	0.200	1	200
F4	Lower number of members and a non-rotated layout are better	Number of patient room bay infills, Non-rotated (NR)/Rotated (R)	0.200	1	200
F5	More repetitive members (fewer different size pieces) is better	Number of different size pieces	0.098	5	100
F6	Lower number of labor hours is better	Labor hours	0.102	3	150
F7	Lower number of total pieces is better	Number of total pieces	0.096	6	75
F8	Lower structural weight is better	Structural weight (psf)	0.105	2	175
F9	Lower structural depth is better	Beam depth (in)	0.099	4	125

The criteria, attributes, and applicable units for CBA are also indicated in Table 33. The criteria indicate what attributes are more favorable. These descriptions are also applicable to the criteria being compared with AHP and PM. These two methods also include cost, which will be more favorable when cost is lower.

The sustainability criteria rewards systems with lower carbon emissions. Future flexibility is based on the number of members and demand to capacity ratios. A lower number of members is desirable because it has less potential for future conflicts with additional openings or mechanical equipment. Lower utilization ratios are more desirable because the members have the capacity to carry extra loads that may be added in the future. For plenum and structural depth, systems with lower depth are better because they can potentially provide more room for mechanical equipment or the extra plenum space can be eliminated and used to increase floor-to-ceiling heights. Figure 96 shows a sample floor section illustrating member depths and usable spaces within the ceiling cavity for gravity system 1a (original composite design). Sections for the remaining systems are included in Appendix B. Plenum coordination involves integration between the structural and mechanical systems. Typical patient room and interior bays are shown with mechanical system overlays in Figures 97-100. These figures also show section locations for plenum depth figures.

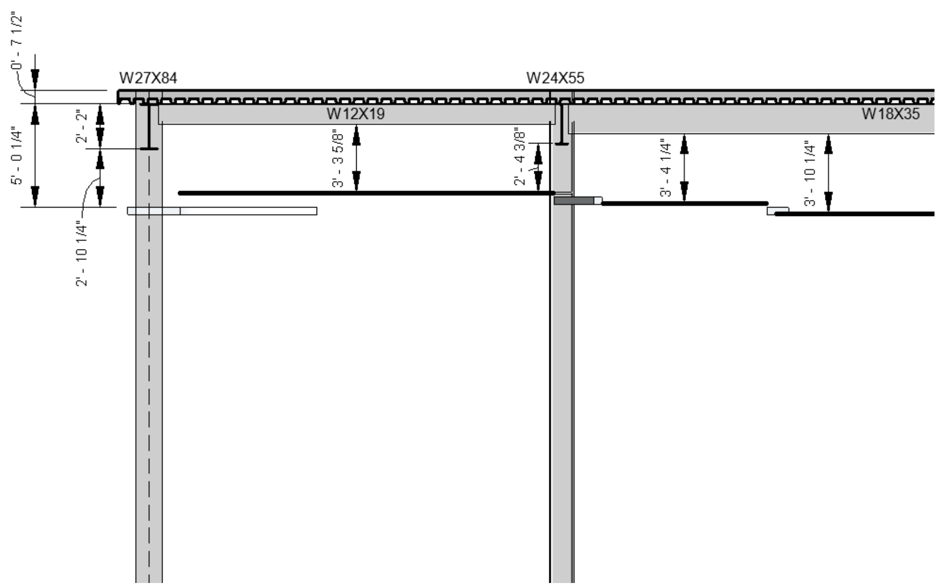


Figure 96: Gravity System 1a Floor Section

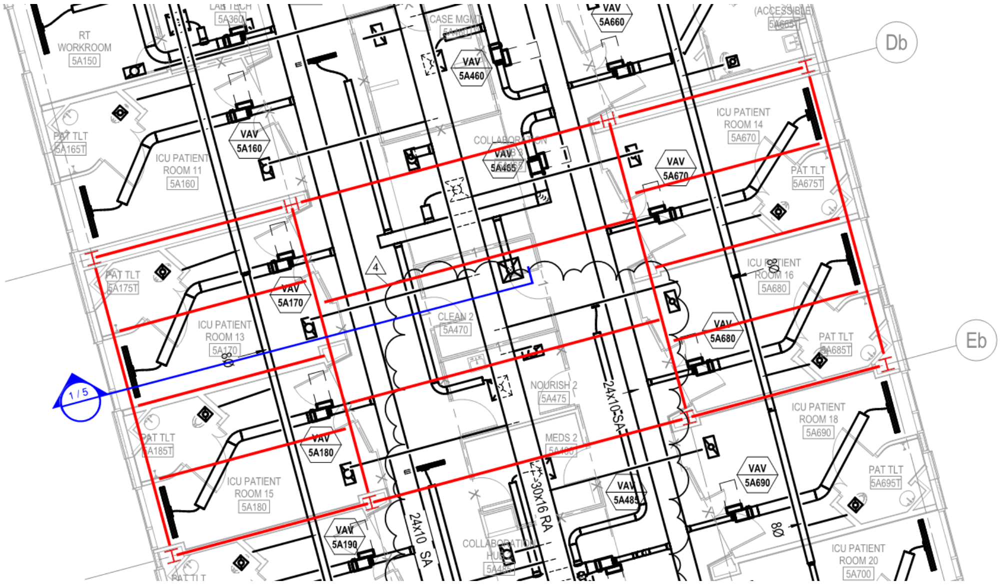


Figure 97: Mechanical Overlay for Original Gravity System Layout

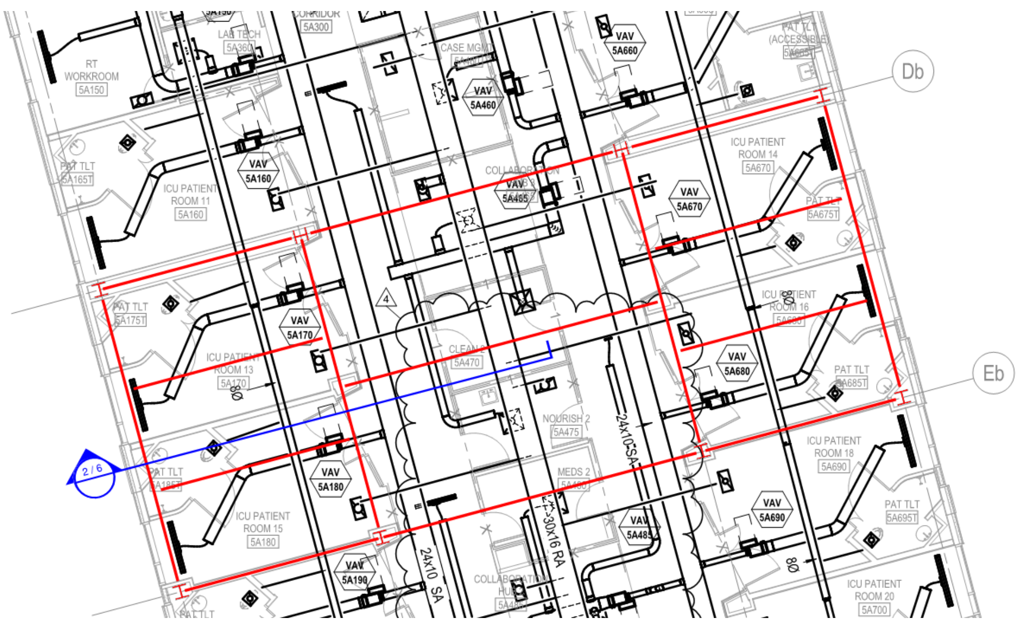


Figure 98: Mechanical Overlay for Layout with Fewer Infills

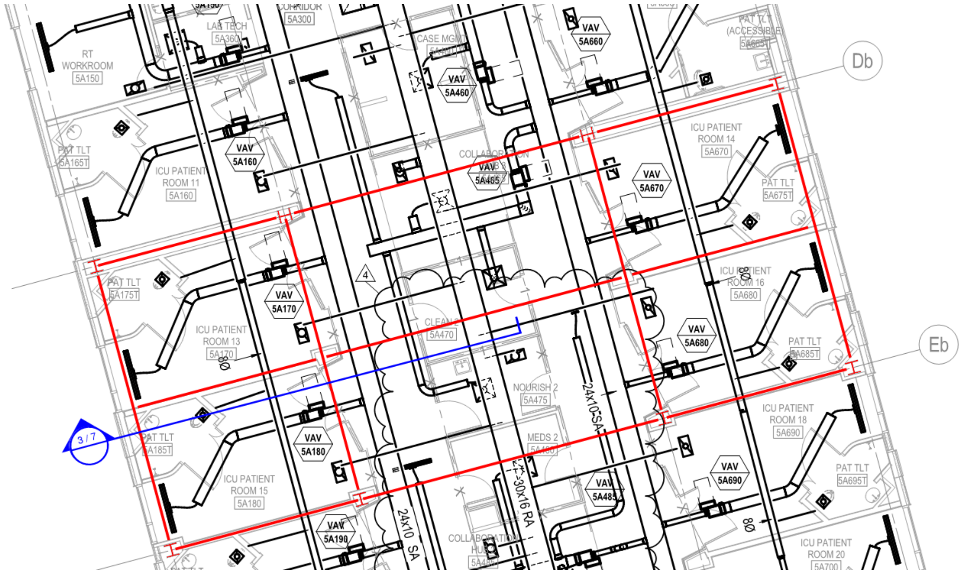


Figure 99: Mechanical Overlay for Modified Layout with Fewer Infills

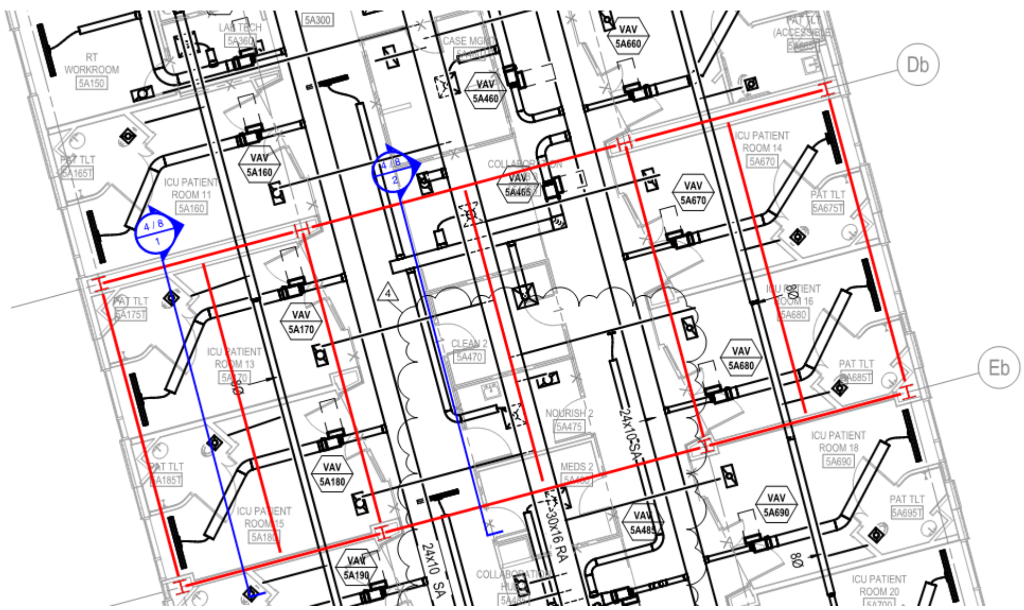


Figure 100: Mechanical Overlay for Rotated Layout

Based on the mechanical overlays, the rotated layout is the worst option for plenum coordination as there is potential for conflict with the large central duct. The systems with the fewest amount of infills and a non-rotated layout are the best. For the repetitive member criteria, systems with a lower number of different size pieces are preferred. The criteria for enhancing/easing erection/construction time is based on labor hours, which should be minimized. Similar to the repetitive member criteria, the layout of the system is more favorable when a lower number of total pieces is involved. Finally, a lower structural member/system weight is favored.

13.7.3 Implementation of AHP, CBA, and PM

AHP, CBA, and PM are used to compare gravity systems 1b through 6, as indicated in Section 8.2. Refer to Section 13.7.1 for notations used in comparisons. Below are sample AHP calculations for comparing the gravity bay iterations in terms of the sustainability subcriterion.

Subcriteria G1: Sustainability (carbon emissions)

C

	1b	2	3	4	5	6
1b	1	5	5	7	1/5	3
2	1/5	1	1	3	1/7	1/3
3	1/5	1	1	3	1/7	1/3
4	1/7	1/3	1/3	1	1/9	1/5
5	5	7	7	9	1	5
6	1/3	3	3	5	1/5	1
Σ	6.88	17.33	17.33	28.00	1.80	9.87

	1b	2	3	4	5	6
1b	0.15	0.29	0.29	0.25	0.11	0.30
2	0.03	0.06	0.06	0.11	0.08	0.03
3	0.03	0.06	0.06	0.11	0.08	0.03
4	0.02	0.02	0.02	0.04	0.06	0.02
5	0.73	0.40	0.40	0.32	0.56	0.51
6	0.05	0.17	0.17	0.18	0.11	0.10

W

	Weights	*C* x *W*	(*C* x *W* $_i$)/W_i
1b	0.231	1.54	6.64
2	0.061	0.37	6.08
3	0.061	0.37	6.08
4	0.030	0.18	6.21
5	0.487	3.41	7.02
6	0.131	0.82	6.24

λ_{max}	6.38		
CR	0.06	<	0.1

The weights show that gravity system 5 is the most favorable alternative in terms of sustainability. The consistency ratio is below 0.1, showing that the comparisons are consistent. This standard was met for all AHP comparisons. The complete set of AHP pairwise comparisons is included in Appendix B. The final AHP results are shown in Table 34. The results indicate that alternative concept 5, the non-composite system with the original layout, is the best system for use in the gravity redesign.

Table 34: Final AHP Comparisons

Criteria	*General*			*Architectural*		*Construction*		*Structural*			*Overall Preference*
Weight	0.1			0.4		0.2		0.3			
Subcriteria	*G1*	*G2*	*G3*	*A1*	*A2*	*C1*	*C2*	*S1*	*S2*	*S3*	
Weight	*0.22*	*0.37*	*0.41*	*0.5*	*0.5*	0.49	0.51	0.32	0.35	0.33	
Concept 1b	0.231	0.028	0.067	0.361	0.108	0.067	0.053	0.028	0.076	0.036	0.129
Alternative Concept 2	0.061	0.147	0.140	0.090	0.195	0.267	0.028	0.147	0.173	0.090	0.135
Alternative Concept 3	0.061	0.324	0.275	0.036	0.332	0.067	0.333	0.324	0.339	0.036	0.202
Alternative Concept 4	0.030	0.324	0.026	0.036	0.064	0.067	0.127	0.324	0.339	0.036	0.122
Alternative Concept 5	0.487	0.028	0.401	0.361	0.108	0.267	0.333	0.028	0.026	0.361	**0.223**
Alternative Concept 6	0.131	0.147	0.091	0.116	0.195	0.267	0.127	0.147	0.046	0.116	0.139

CBA comparisons are shown in Tables 35 and 36. The results indicate that alternative concept 6 is the best system for use in the gravity redesign, followed by alternative concept 5. This reveals a discrepancy between the AHP and CBA results; however, alternative concept 6 has a higher cost than alternative concept 5. To compare these two systems, Figure 101 shows a plot of the total IoA and the sum of the material costs for the three typical bays. This scenario requires decision-makers to determine if the value of the advantages outweighs the additional costs.

Table 35: Final CBA Comparisons Part 1

	System 1b			*Alternative System 2*			*Alternative System 3*		
Factor	Attributes	Adv.	IoA	Attributes	Adv.	IoA	Attributes	Adv.	IoA
F1	14804	13% less	20	15722	7% less	5	15379	9% less	10
F2	19, 0.4	37% lower UR	10	16, 0.4	16% less, 37% lower	30	15, 0.44	21% less, 30% lower	40
F3	14”	33% less depth	200	18”	14% less depth	100	21”	--	--
F4	3, NR	Non-rotated	67	2, NR	Non-rotated	133	1, NR	Non-rotated	200
F5	6	--	--	5	17% less	100	6	--	--
F6	33.60	1.3% less	30	34.03	--	--	31.69	7% less	150
F7	19	--	--	16	16% less		15	21% less	75
F8	88.38	--	--	74.56	15.6% less	70	74.13	16% less	105
F9	14”	33% less depth	125	18”	14% less depth	63	21”	--	--
Total	--	--	452	--	--	501	--	--	580

Table 36: Final CBA Comparisons Part 2

	Alternative System 4			*Alternative System 5*			*Alternative System 6*		
Factor	Attributes	Adv.	IoA	Attributes	Adv.	IoA	Attributes	Adv.	IoA
F1	16958	--	--	13090	23% less	25	14889	12% less	15
F2	15, 0.35	21% less, 44% lower	50	19, 0.63	--	--	16, 0.52	16% less, 17% lower	20
F3	21”	--	--	14”	33% less depth	200	18”	14% less depth	100
F4	1, R	--	--	3, NR	Non-rotated	67	2, NR	Non-rotate d	133
F5	6	--	--	5	17% less	100	5	17% less	100
F6	32.69	4% less	60	31.78	6.7% less	120	32.57	4.3% less	90
F7	15	21% less	75	19	--	--	16	16% less	56
F8	61.41	31% less	175	86.19	2.5% less	35	73.50	17% less	140
F9	21”	--	--	14”	33% less depth	125	18”	14% less depth	63
Total	--	--	360	--	--	672	--	--	**717**

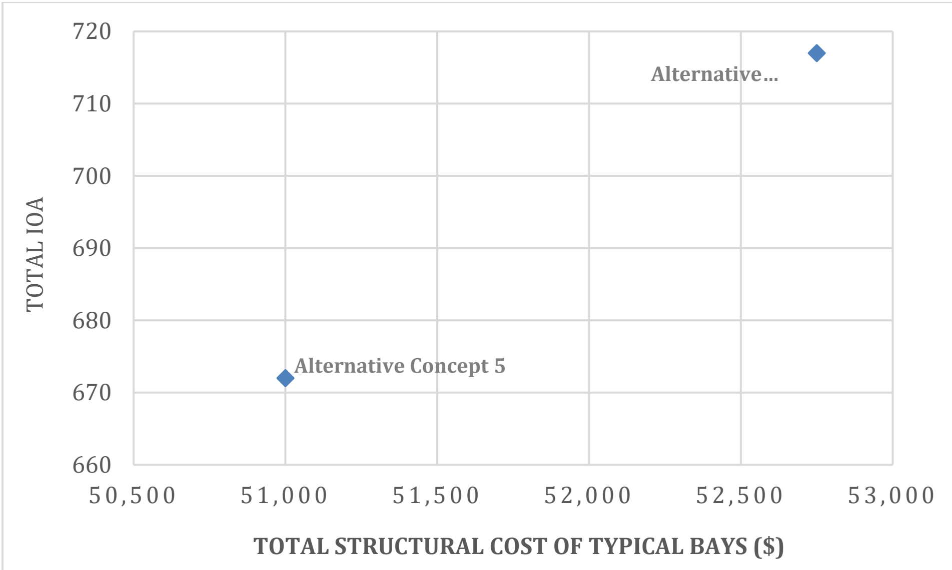


Figure 101: CBA Cost-Advantage Comparison

Finally, the PM comparisons are shown below.

Criteria	Weight	Baseline: 1B	2	3	4	5	6
G1	0.022	0	-1	-1	-1	1	-1
G2	0.037	0	1	1	1	-1	1
G3	0.041	0	1	1	-1	1	1
A1	0.200	0	1	1	-1	1	1
A2	0.200	0	1	1	-1	0	1
C1	0.098	0	1	0	0	1	1
C2	0.102	0	-1	-1	-1	1	-1
S1	0.096	0	1	1	1	0	1
S2	0.105	0	1	1	1	1	1
S3	0.099	0	1	1	-1	1	1
Σ(Weight x Score)		0	0.752	0.654	-0.426	0.63	0.752

Criteria	Weight	2	3	5	6
G1	0.022	0	1	1	1
G2	0.037	0	1	-1	1
G3	0.041	0	1	1	-1
A1	0.200	0	-1	1	-1
A2	0.200	0	1	-1	0
C1	0.098	0	-1	0	0
C2	0.102	0	1	1	1
S1	0.096	0	1	-1	1
S2	0.105	0	1	-1	1
S3	0.099	0	-1	1	-1
	Σ(Weight x Score)	0	0.206	0.026	0.022

Criteria	Weight	3	5
G1	0.022	0	1
G2	0.037	0	-1
G3	0.041	0	1
A1	0.200	0	1
A2	0.200	0	-1
C1	0.098	0	1
C2	0.102	0	1
S1	0.096	0	-1
S2	0.105	0	-1
S3	0.099	0	1
	Σ(Weight x Score)	0	**0.124**

Initially, systems 2-6 were compared to system 1b, which was used as the baseline. The system with the lowest rating was removed from further consideration, and the system with the highest rating became the baseline for the next PM comparison. This process was repeated until a final design emerged as the best selection. The results agree with the AHP analysis as the non-composite design with the original layout was shown to be the most preferred system.

PM was also used to verify the decision made during the initial alternative gravity system study in Section 7.2. The comparisons utilize updated system and cost information included in Appendix A. A notable change includes modifications made to the flat slab depths as described in Section 10.2. The process shown below results in the selection of the composite system with fewer infills. This agrees with original decision to move forward with a steel system for the gravity system redesign.

Criteria	Weight	Baseline: Existing Composite Design	Composite with Fewer Infills	Flat Slab	One-way Pan Joists
G1	0.022	0	-1	1	1
G2	0.037	0	1	-1	-1
G3	0.041	0	1	1	-1
A1	0.200	0	1	1	1
A2	0.200	0	1	1	1
C1	0.098	0	1	-1	1
C2	0.102	0	1	-1	-1
S1	0.096	0	0	1	1
S2	0.105	0	1	-1	-1
S3	0.099	0	-1	1	1
Σ(Weight x Score)		0	0.662	0.316	0.43

Criteria	Weight	Baseline: Composite with Fewer Infills	One-way Pan Joists
G1	0.022	0	1
G2	0.037	0	-1
G3	0.041	0	-1
A1	0.200	0	1
A2	0.200	0	-1
C1	0.098	0	1
C2	0.102	0	-1
S1	0.096	0	-1
S2	0.105	0	-1
S3	0.099	0	1
Σ(Weight x Score)		**0**	-0.162

13.8 Decision-Making Case Study Result Comparison

Based on the results of the MCDM application to the Mercy Health Muskegon gravity redesign case study, the gravity system rankings for each method are as follows:

AHP ranking
1. Non-composite design with original layout
2. Composite with fewer infills and modified layout
3. Non-composite with fewer infills
4. Composite with fewer infills
5. Original composite design (modified to meet vibration requirements)
6. Composite with fewer infills and rotated layout

CBA ranking
1. Non-composite with fewer infills
2. Non-composite design with original layout
3. Composite with fewer infills and modified layout
4. Composite with fewer infills
5. Original composite design (modified to meet vibration requirements)
6. Composite with fewer infills and rotated layout

PM ranking
1. Non-composite design with original layout
2. Composite with fewer infills and modified layout
3. Non-composite with fewer infills
4. Composite with fewer infills
5. Original composite design (modified to meet vibration requirements)
6. Composite with fewer infills and rotated layout

The AHP and PM rankings are identical. There is some discrepancy between these two methods and the CBA rankings. CBA ranks the non-composite design with fewer infills as the preferred system, while this is the third-ranked system in AHP and PM. CBA ranks the non-composite design with the original layout second, which falls just short of the top ranking it received in AHP and PM; however, a cost-advantage comparison between the two methods, since CBA does not consider cost, reveals that the original layout has a lower total IoA but a lower cost, as well. Since cost is a significant factor in large healthcare projects, it is reasonable that the non-composite design with the original layout could also be considered the most preferred system based on the combined CBA analysis and cost-advantage comparison. Since the non-composite system with the original layout consistently received high preferences with AHP, CBA, and PM, this system is recommended for use in the structural redesign of the Mercy Health Muskegon healthcare facility.

13.9 Decision-Making Case Study Summary

Overall, the results of the AHP, CBA, and PM applications to the case study were very similar, showing that any of the three methods could be used as a reliable tool to select structural systems in healthcare facilities. Each process has advantages and disadvantages. Each requires input from stakeholders to determine the project goals and which criteria are the most important; however, this leads to a lot of subjectivity. The weights are calculated from subjective decisions made by stakeholders or in this case the industry professionals who responded to the survey, which could potentially lead to bias. Additionally, many of the comparisons themselves are subjective. For example, determining which system provides the greatest degree of flexibility or plenum coordination can be less straightforward than determining which system has a lower weight. These decisions can greatly change the outcome, so it is important to be consistent throughout all comparisons.

In terms of complexity, PM proved to be the simplest method, which is why it was also used to verify the initial, broad gravity system selection. The system comparisons rely only on values of 1, 0, and -1, making it quick and easy to apply. On the other hand, AHP pairwise comparisons are significantly more involved, especially with a large number of criteria and alternatives. Finally, CBA has an easy to understand format, but the results were inconsistent with AHP and PM. Cost must also be considered separately, requiring stakeholders to acknowledge tradeoffs between advantages and cost. The survey showed that industry professionals with healthcare project experience do not often rely on these formal decision-making methods but would be open to the idea if they proved to be uncomplicated and effective. The simple and reliable PM seems to be the most suitable method to meet these requirements.

Healthcare facilities are complex and lead to many complicated decisions throughout the design process. These decision-making methods would be useful for providing a transparent analysis that could lead to more open-minded decision-making processes and innovative designs. Although the industry professionals confirmed in the survey that healthcare parameters can greatly vary between projects, the decision-making criteria can be modified to meet the needs and goals of individual healthcare projects. This case study shows the usefulness of AHP, CBA, and PM for selecting a structural system that promotes sustainability, constructability, system integration, flexibility, and most importantly, a patient-centered healing environment.

14.0 Conclusion

The Mercy Health Muskegon hospital addition gravity and lateral systems were redesigned for a change in location from Muskegon, MI to Fort Lauderdale, FL, a location where the Trinity Health system has other healthcare facilities. The lateral system was changed from a steel braced frame and moment frame system to a reinforced concrete shear wall system to control drift from hurricane region wind loads. Multi-criteria decision-making methods were used to determine the most beneficial gravity system. The goal was to select a system that increased acoustic performance, considered sustainability, and was designed for system integration. The most preferred system was a non-composite gravity system that implements the original layout; therefore, the gravity structure was redesigned from a composite steel system to a non-composite steel system. The final structural redesign resulted in $500,000 cost savings. An acoustic design solution for the PACU was also proposed. The PACU patient areas would be separated into pods of two bays by insulated partitions to reduce noise and provide privacy. Prefabricated bathroom pods were also suggested for the private patient rooms. The prefabricated bathrooms would reduce the construction schedule by approximately 6 months, resulting in considerable cost savings. The redesign as a whole resulted in a system that met priorities of a patient-centered healing environment, sustainability, and system integration.

14.1 PSU AE – ABET 2.3

The proposed design solutions place an emphasis on the impact on architectural features, MEP systems, and construction processes. The gravity system redesign considered criteria such as future flexibility, plenum coordination, and enhancing/easing construction/erection time. The lateral system redesign also focused on placing shear walls in areas where they would have the least architectural impact and maintain flexibility for future renovations. The PACU acoustic analysis also considered how adding partitions would affect circulation. The prefabrication study discusses the impact on the construction schedule and sequencing.

14.2 PSU AE – ABET 2.4

The proposed design solutions also consider factors such as public health, welfare, sustainability, and economic impact. Vibration and acoustic considerations strive to prove a high degree of patient welfare. The acoustic analysis also investigated the effects that partitions would have on staff flow and the ability to maintain a quality standard of care without sacrificing safety. The gravity redesign addressed sustainability efforts by striving to reduce carbon emissions. Sustainability was further addressed in the prefabrication analysis. The use of modular bathrooms reduces material waste by moving construction to a controlled environment. This process would significantly reduce the construction schedule, allowing earlier occupancy and revenue generation. This would build upon the costs saved from the redesigned gravity system.