Background

The design of structural slabs for the St. Paul building was completed to understand the impact of alternative structural systems to the bottom-line costs, the critical path, and the problems encountered onsite. Post-tensioned slabs have been shown to be inferior in all of these categories and have proven to be a real headache in the field at Charles Commons. However, the best way to analyze a design change is to measure its beneficial/negative effects on the other half of the building systems. Exterior skin, interior finish, mechanical ductwork, plumbing, fire protection, and electrical systems are all impacted by the structure. The MEP portion of the project is most affected by the structural slabs since the MEP runs adjacent to the slabs and therefore, the MEP coordination would be the most beneficial analysis.

In the interview with the owner's representative, Mike DiProspero, the problems with the existing MEP coordination were discussed. First, the MEP coordination started late. MEP coordination has been assumed to be optimal when beginning during MEP design to prevent designing the systems twice, as learned on the UW Research & Technology building in the interview with John Whitlow. On Charles Commons, MEP coordination began after design was completed and subcontractors were awarded contracts.

Secondly, the MEP coordination suffered from a lack of direction on the part of its participants. Initially, MEP coordination was the task of the mechanical/electrical engineer. When submittals were completed, they would be used to coordinate the environmental systems. Problems in obtaining submittals and cooperation delays caused more of the MEP coordination to be completed in the field. Thus, a MEP superintendent was brought on-board late in the process in the attempt to salvage the coordination. Later in the project, the ceiling heights were lowered one foot in all of the St. Paul building spaces anyway.

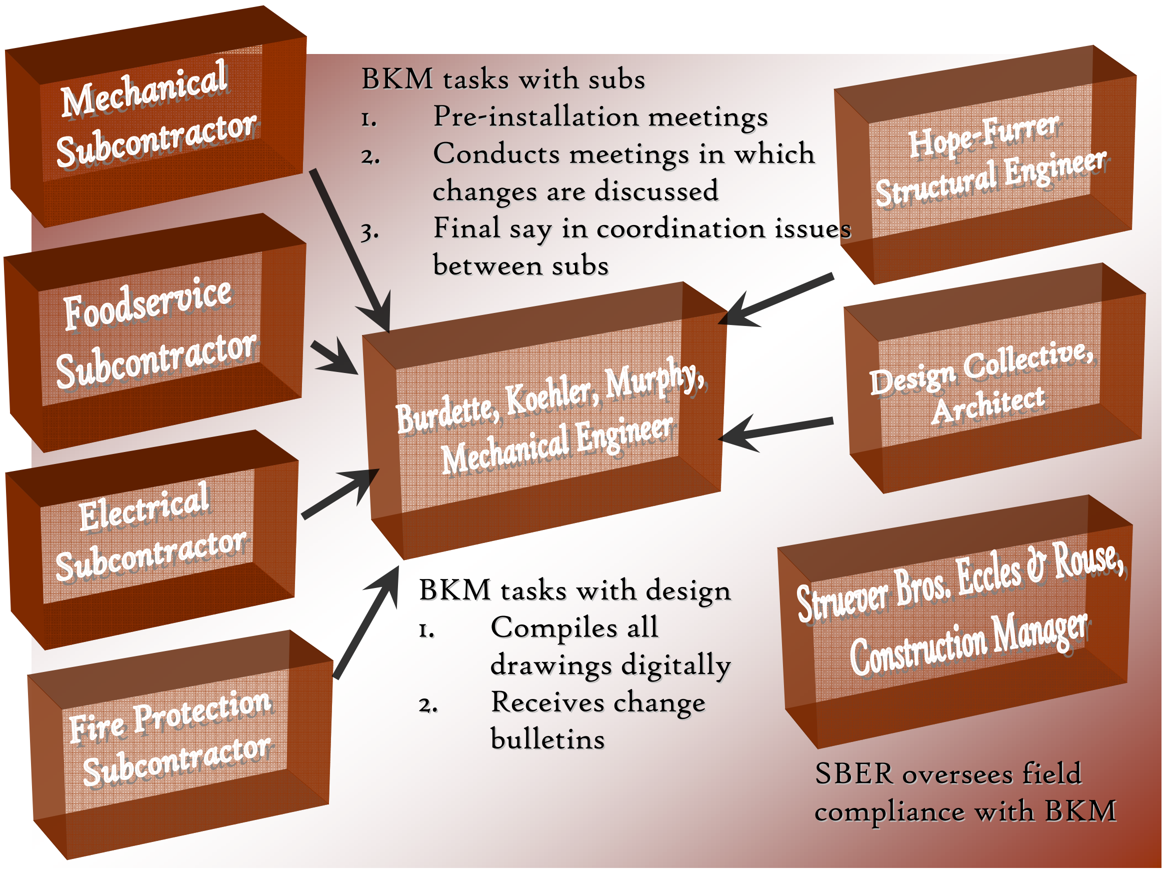


Figure 2: MEP Coordination process at Charles Commons

Finally, the MEP coordination process was performed during meetings by overlaying 2D drawings and completing a few mock-ups. The three-dimensional MEP digital modeling performed on the UW Research & Technology building proved to be very successful, although the process was not introduced until 50% development drawings. I believe that the complicated nature of the floor layouts on the first four floors would lend itself well to 3D digital modeling.

Analysis Goals:

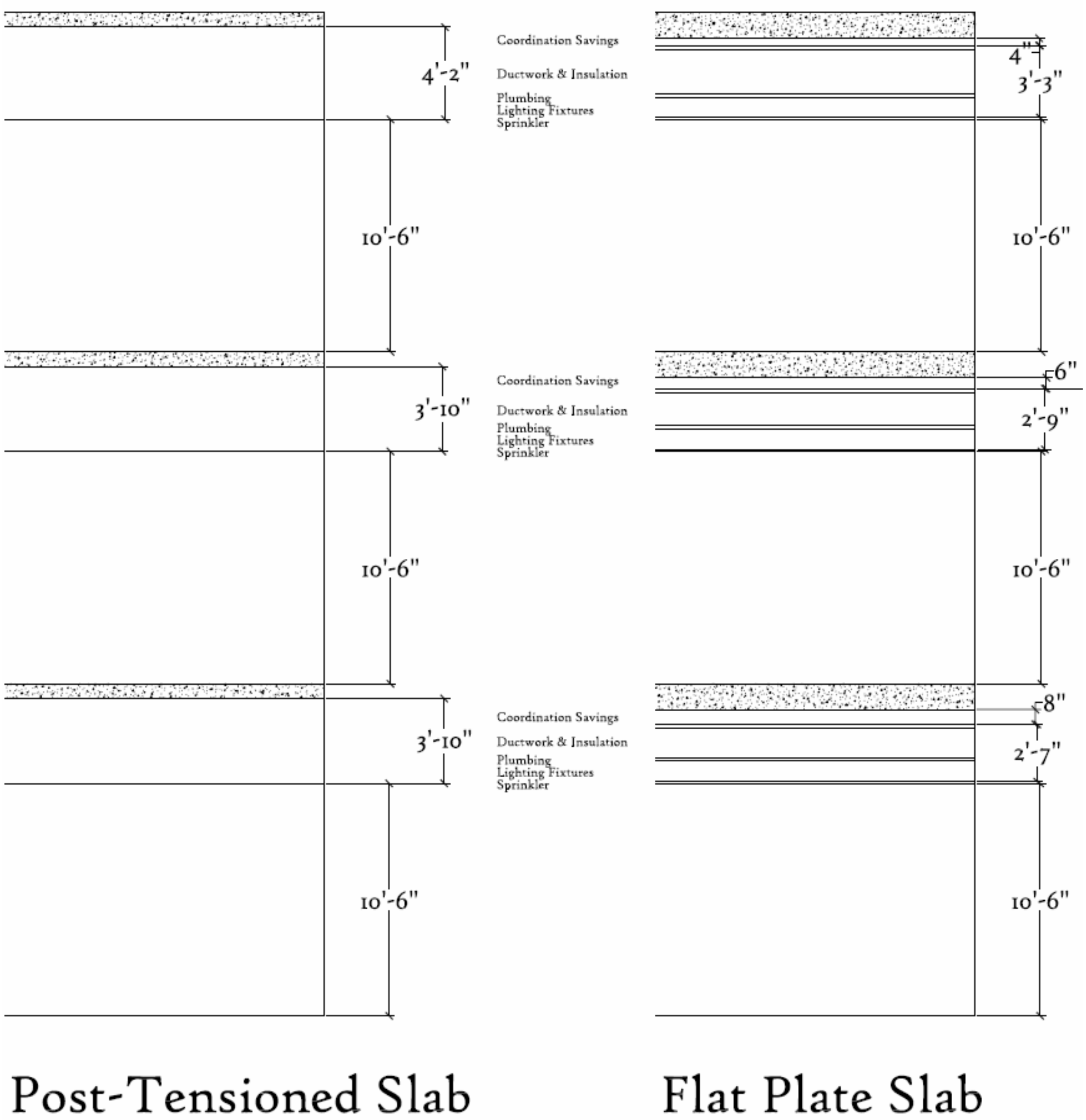
- *2-D Analysis: identify the areas in which ductwork can be redesigned to minimize conflict with other ductwork, columns, walls, ceilings, and piping*
- *Ductwork Sizing: size the ductwork, estimate the pressure drops, and determine the cost variations*
- *3-D Analysis: model the structural components (including both column plans), the HVAC ductwork and units, and the plumbing*
- *4-D Analysis: sequence the structural and mechanical components of the 3-D model to determine the system constructability*
- *Digital Modeling Comparison: compare the different model analyses to determine the best application for JHUCC*

The ultimate goal of the MEP analysis is to demonstrate the flexibility allowed with the alternative structural systems. The sections below show the “goal” plenum sizes and approximations of where the different systems will reside in the plenum. The MEP analysis performed here will validate the flat plate slab as the “best-value” option as compared to the existing post-tensioned slabs.

Plenum Analysis

The post-tensioned system currently allows 3’-10” and 4’-2” plenum space and 10’-6” ceilings. The plenum can be divided and analyzed by the maximum height each of the following systems: HVAC ductwork, plumbing, and electrical/sprinkler. Since the electrical fixtures in the building were already specified with 5 ½” maximum heights and sprinkler heads do not conflict with the lighting grid, the electrical/sprinkler space is allocated 6” of space. In the proceeding 3-D analysis, piping larger than 6” in diameter was modeled and checked to not conflict with the ductwork. Therefore, the plumbing space allocated is assumed to be 6”.

Since insulation is integral with ductwork, an extra 2 inches was allocated for this purpose. This leaves 18” of ductwork on the 1^{st} floor, 20” on the 2^{nd} floor, and 24” on the 3^{rd} floor. The aspect ratio was increased where individual ductwork sizes exceeded these parameters. However, the majority of the ductwork needed rerouted to prevent exceeding the ductwork height requirement.



Spatial Requirements

Both the St. Paul and Charles buildings were designed for the highest efficiency with space. The structure was designed post-tensioning to lower the floor-to-ceiling heights, the apartments had their own HVAC units, and the columns were designed far apart for an open floor plan. These measures allowed the Charles building to remain below the maximum building height.

The St. Paul building's first three floors introduce seemingly insurmountable complication to the Charles Commons project. The integration of a bookstore and

dining hall with the apartments render the placement of vertical risers difficult. In order to maintain large retail square footage, the mechanical and electrical rooms were minimized to near-closet proportions. Bathroom, kitchen, grease hood, and janitor's closet exhausts wreak havoc with the overhead supply and return ductwork. The open ceiling space in the dining hall, that features oval ductwork for architectural appeal, cannot be penetrated with rectangular main branch ductwork. Outdoor air intake is limited to the third floor northwest intake and the fourth floor courtyard intake. In addition, the 8" post-tensioned slab requires 6'x6' drop-caps for punching shear around all of the columns, which intrude on the limited plenum space in small corridor spaces.

St. Paul Mechanical System

Parallel all-air systems and fan coil units supply the first three floors of the St. Paul building (4 air-handling units and 2 fan coil units). Two chillers and a cooling tower is located in the mechanical penthouse on the roof of the building. Smaller, localized fan-coil units are used in the dormitory units. The air-handlers work under a variable frequency drive and contain all of the standard compartments. The fan coil units are belt drive horizontal chilled water blower coil units and are fed from the chilled water coils from the penthouse.

At this point, different mechanical systems were considered, including the implementation of a DOAS system. Although this system meets many of the requirements of ASHRAE and is currently being tested at Penn State, many of the long-term effects of the DOAS system are unknown. Since the system is relatively unknown in the Baltimore market and there are barriers in finding a supplier of the DOAS, the possibility was stricken. I believe at a later date, the benefits of DOAS will be proven and it can be exploited on buildings with height requirements, such as Charles Commons. Since one of the themes of this thesis strives for decreasing lifecycle costs, investment in a DOAS system would not be conservatively wise.

Figure 6.1: Typical AHU courtesy of York International.

Air-Handlers

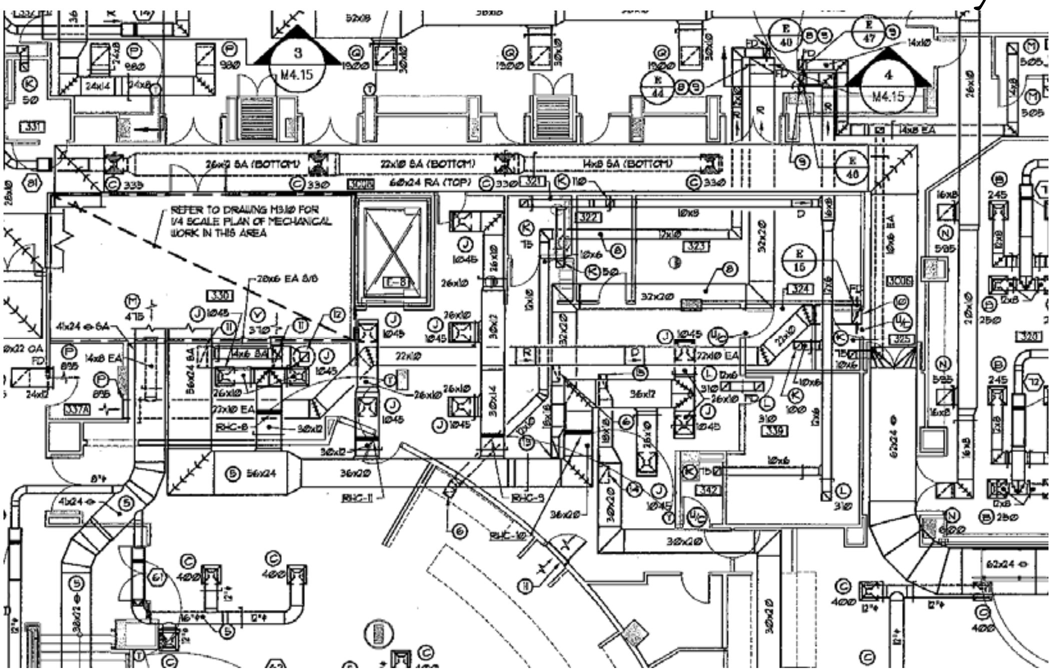
AHU #	York Model #	Service (floor)	Capacity (cfm)	Min OA (cfm)	AHU Size (wxh) in.	Room Size (lxwxh) ft
AHU-4	500	Bookstore (2^{nd})	25055	11200	125 x 95	48x36x10
AHU-5	305	Dining (2^{nd})	12900	9000	103 x 64	48x36x10
AHU-6	215	Kitchen (3^{rd})	10450	10450	91 x 55	32x15x10
AHU-7	305	Meeting (3^{rd})	14800	14800	103 x 64	36x21x10

Figure 6.2: Typical fan-coil unit courtesy of Magic Aire.

Fan-Coil Units

FCU #	Magic Aire #	Service (floor)	Capacity (cfm)	Min OA (cfm)	FCU Size (wxh) in.	Room Size (lxwxh) ft
FCU-1	60-HBAW-6	Lobby (1^{st})	2500	250	72 x 48	48x36x10
FCU-3	24BVW	Bkstr. (2^{nd})	400	0	48 x 48	16x14x10

Two-Dimensional MEP Coordination Analysis



Two-dimensional MEP coordination background

A two-dimensional MEP coordination analysis begins with the review of the latest issue of the contract documents. There are two ways of reviewing the contract documents for MEP coordination. The pre-emptive solution in 2-D MEP coordination is for the drawings to be coordinated in 2D CAD through design development meetings to prevent overlapping layers. Typically this solution would involve the contractors during a Design-Build delivery and exclude their constructability analyses during a Design-Bid-Build delivery. The lack of construction expertise in the design phase limits most projects to the latter solution: the paper review.

The paper review occurs when contractors are introduced to the project at 100% construction documents. Contractors hold MEP coordination meetings onsite to determine the sequencing of the MEP trades and make decisions on plenum conflicts. This form of MEP coordination is the most frequent in construction.

Using the mechanical plans, areas in which ductwork crossed with other ductwork were analyzed and a solution was proposed in each of the six instances. Increasing the aspect ratio of the ductwork was not used in this analysis since most ductwork was at least 2:1 to 4:1. Any increases in this value could severely affect air flows and most of the limiting ductwork were already 3:1. These solutions were later checked in 3D. The timeframe for the 2D analysis was 4 hours.

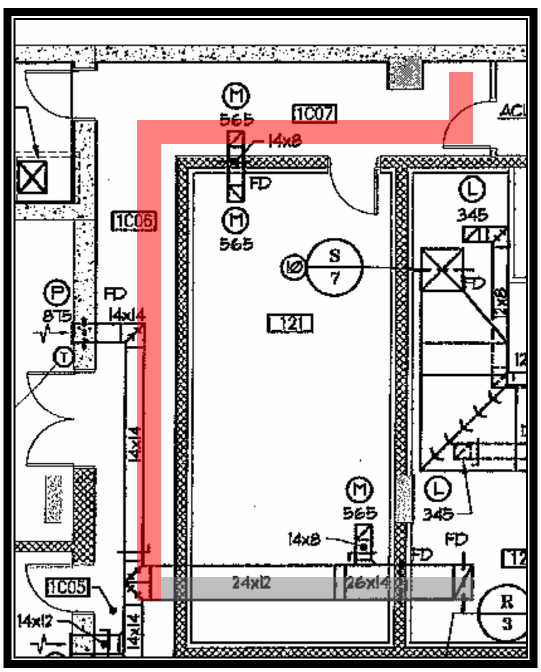
Ductwork Rerouting Issues

E1, Exhaust from 1st floor

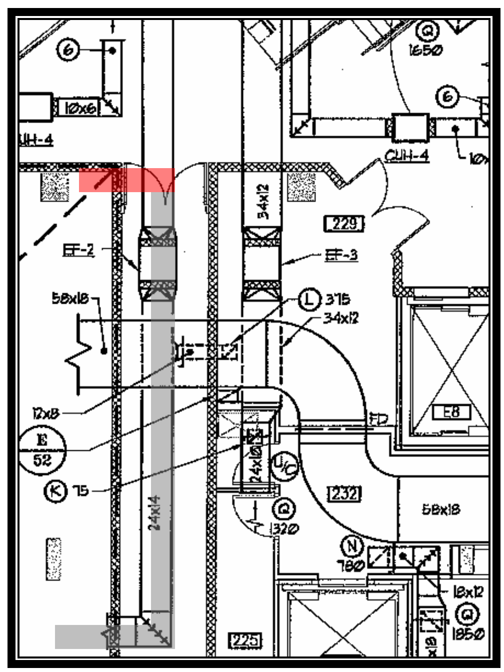
The exhaust that serves the bathrooms, electrical room, mechanical room, and storage areas of the first floor exits the building on the north elevation of the 2nd floor. On the second floor, the 24"x14" crosses a 58"x18" supply for the second floor, which affects the minimum possible height for the second floor (32"). The rerouting of this exhaust through the corridor on the first floor bypasses the oversized 58"x18" duct shrinking the plenum from 32" to 18". The floor penetration would not be possible with the post-tensioned structural slab since a post-tensioning tendon spans column to column in the exact area where the new duct riser is constructed. This rerouting of ductwork results in one more turn and a slightly longer branch.

The ductwork shown in grey is the omitted ductwork from the original plan and the areas shaded red is where the ductwork was rerouted. Ductwork is formally resized in the calculations following this section.

First Floor



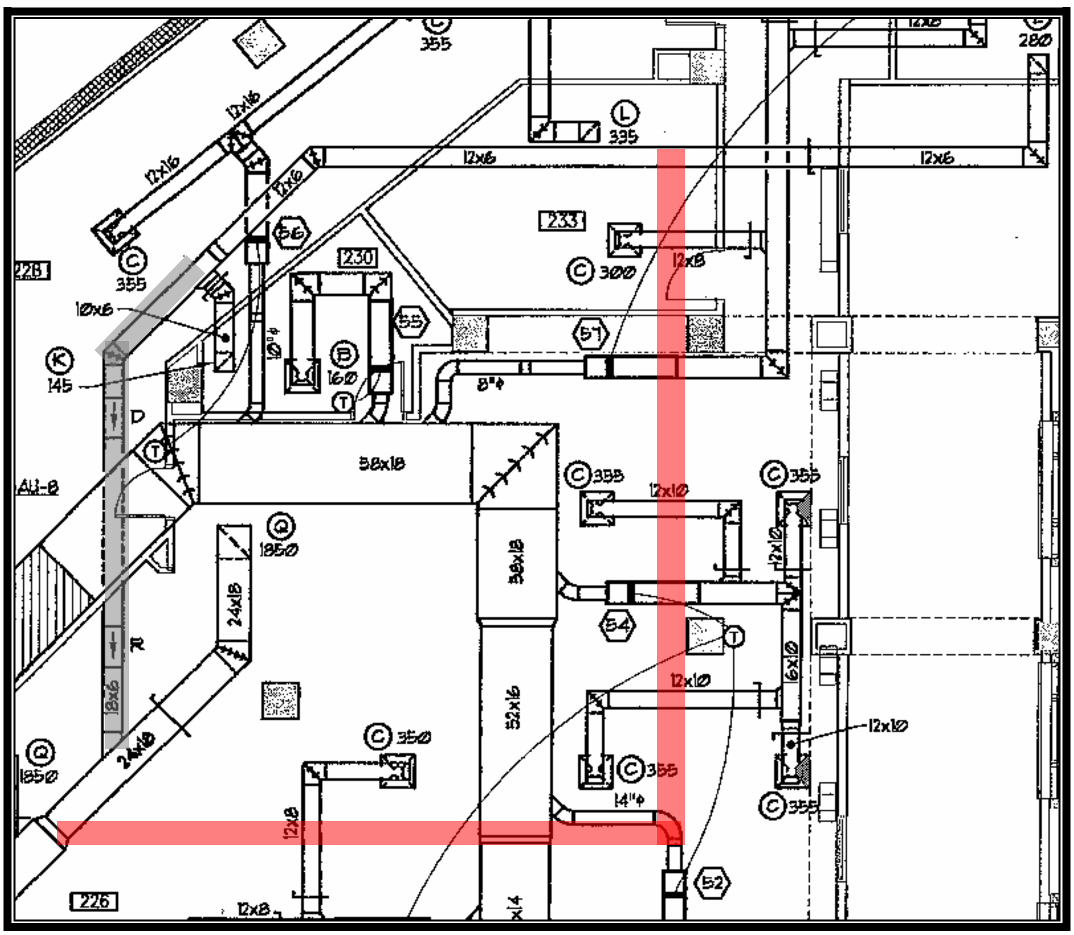
Second Floor



EB2, Return from 2nd floor bookstore

The return duct that criss-crosses along the bookstore plenum on the second floor serves the offices and bookshelves. The return from 2nd Floor bookstore spaces was rerouted to prevent crossing the 58"x18" supply duct with a 18"x6" duct. Instead, the 18"x6" duct will cross the supply later in its run at the 48"x14" size. The total ductwork length will increase significantly and the ductwork was sized larger to accommodate this. This rerouting of the ductwork decreases the HVAC from 24" to 20".

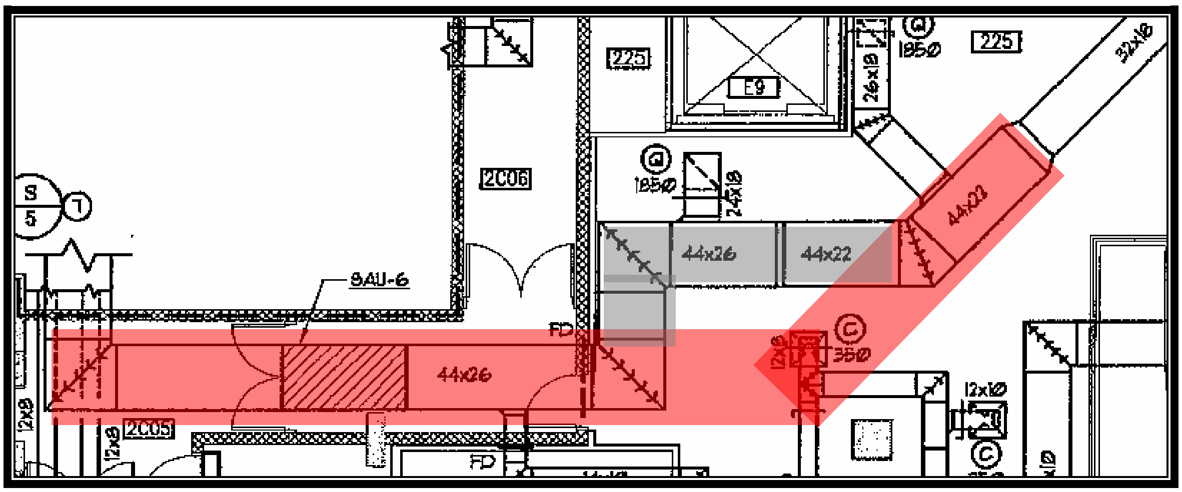
Second Floor



EB2.1, Main branch return from 2nd floor bookstore

The main branch of the return from the second floor bookstore was downsized to 18" to accommodate a concentrated area of plumbing and ductwork. To offset the increase of aspect ratio from 2:1 to 3:1, the ductwork was straightened to one 45-degree turn, saving two 90-degree turns.

Second Floor



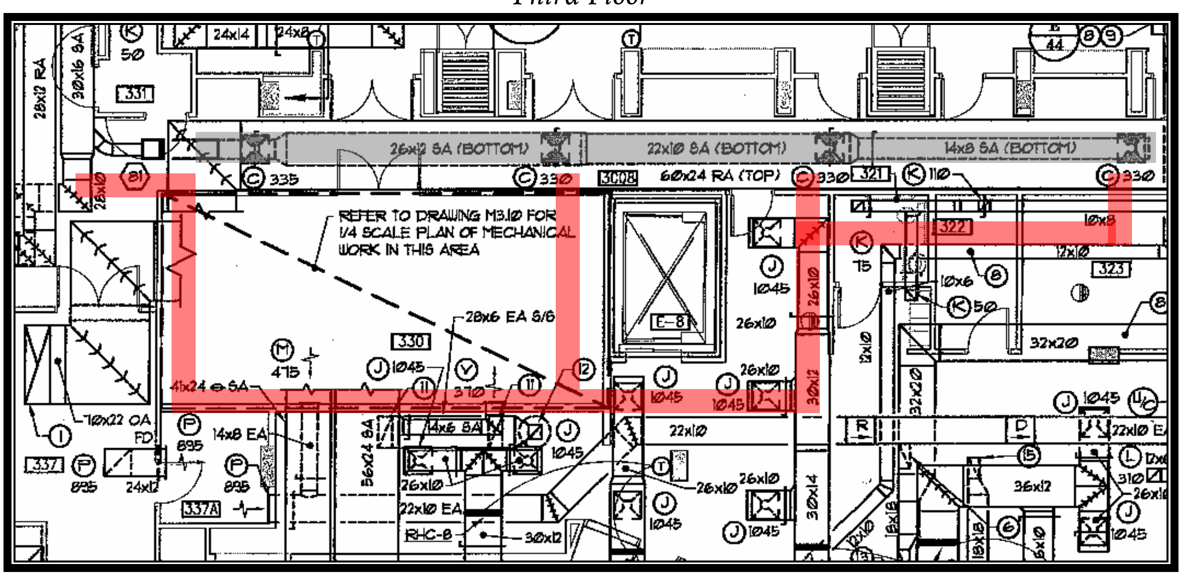
S3, 3rd floor conference corridor supply

The supply for the conference corridor was the single-most problematic MEP coordination issue. The 26"x12" supply needs to distribute conditioned air through four diffusers and pass under a monstrous 60"x24" dining hall main branch return duct. The following are possible routes that were eliminated due to conflicts:

1. Route the supply through the conference room
2. Route the return through the kitchen
3. Decrease the height of the supply
4. Decrease the height of the return
5. Route the return through the conference room

After the elimination of the previous routes, the supply was routed through the mechanical room and along northern edge of the kitchen. This caused an adjustment from ceiling-mounted to wall-mounted diffusers and adjusted the locations of the diffusers by a few feet. These adjustments were necessary to decrease the original height of ductwork from 36" to 24" on the third floor.

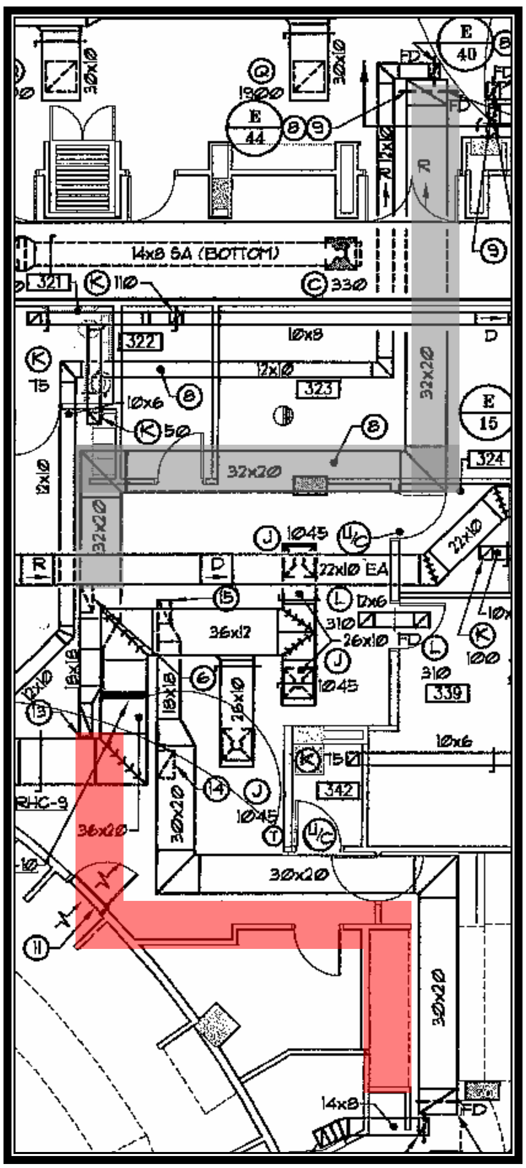
Third Floor



E3.1, Hood exhaust from 3rd floor kitchen

Exhaust from kitchen (grease hood exhaust) was moved to align with grease ductwork at the servery. The adjustment changed the arrangement of duct risers in two of the full-building access risers. The re-routing allowed the 32"x20" exhaust ductwork to utilize a nearly empty riser to move air that would have been otherwise built under a 60"x24" return duct. The flexibility of the flat-plate slab played into the routing by allowing a larger duct riser.

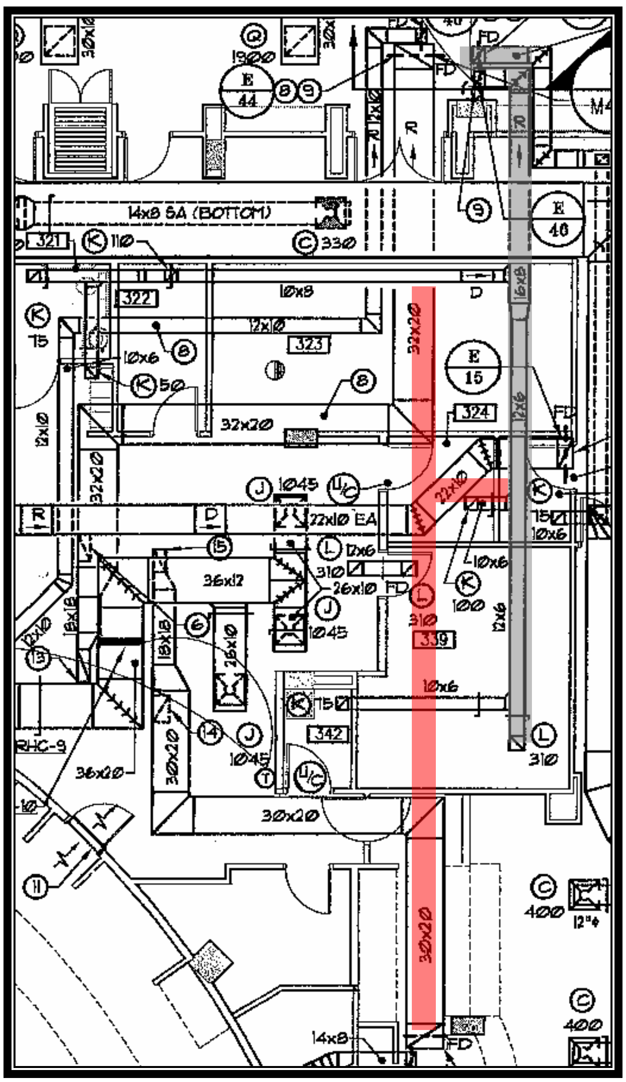
Third Floor



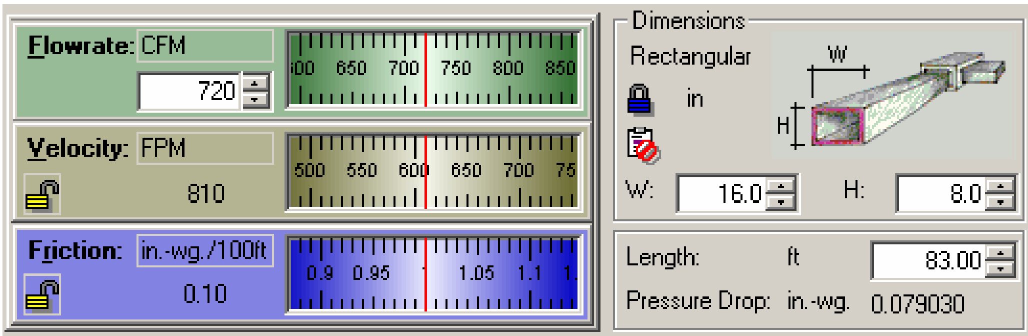
E3.2, Bathroom/Office exhaust from 3rd floor kitchen

Exhaust from the offices and bathrooms (non-grease) in the kitchen was re-routed to connect with the newly-amended E-3.1 ductwork. This allowed yet another piece of ductwork to avoid the large 60"x24" main branch return. In addition, less ductwork is employed to make the connection with the adjoining 32"x20" ductwork, which helps keep the ductwork sizes low.

Third Floor



Mechanical Ductwork Sizing



Methodology

The mechanical ductwork is designed according to the limits of the flat-plate slab and conservation of mass flow. The following are approximately six variables that are associated with ductwork sizing:

- Air Flowrate (cfm)
- Air Velocity (fpm)
- Friction Losses (in.-wg/100ft)
- Equivalent Diameter Dimensions (in)
- Equivalent Length of Straight Duct (for turns)
- Pressure Drop (in-wg.)

These six variables are necessary to compare ductwork branches and design equivalent branches. Variables such as air velocity, friction losses, and the number of turns are subject to change minimally during design and all steps are taken to maintain equivalence with the original system. For comparison sake, the pressure drop will be analyzed in the existing and revised conditions to arrive at simple conclusions. The pressure drop is the measure of the aggregate loss of air volume along the length of the duct branch.

Applications

Two tools were used to calculate the mechanical ductwork rerouting: a ductolator and Marinsoft Duct Calculator. The ductolator is a rotating disc device that compares friction losses, velocity, flowrate, equivalent duct diameter, and duct dimensions. The back of the ductolator has approximate equivalent length of straight duct for different ductwork turns. For instance, conventional 90-degree turns with turning vanes in the horizontal are 25' and in the vertical are 15'.

The screenshot shown above is the Marinsoft Duct Calculator, which calculates everything that the ductolator can and uses the length of the ductwork to calculate the pressure drop in the individual ductwork branches. The Duct Calculator software is calibrated to the accepted values of 406 in.-wg. atmospheric pressure, 68 deg-F temperature, and 0.0751 lb/ft^3 air density. Galvanized steel, continuously rolled, spiral seams with a roughness coefficient of 0.00354 in was used, corresponding with the existing ductwork material.

Equations

1. The velocity of air in a ventilation duct can be expressed in imperial units:

$$v = 144 * q / wd$$

where:
v = air velocity (ft/min)
q = air flow (cfm)
w = width of duct (inches)
d = width of duct (inches)

2. The overall pressure loss in ducts can be expressed as:

$$dpt = dpf + dps + dpc$$

where
dpt = total pressure loss in system
dpf = major pressure loss in ducts due to friction
dps = minor pressure loss in fittings, bends etc.
dpc = minor pressure loss in components as filters, heaters etc.

3. Major pressure loss in ducts due to friction can be expressed as

$$dpf = R * L$$

where
R = duct friction resistance per unit length
L = length of duct(ft)

4. Duct friction resistance per unit length can be expressed as:

$$R = \lambda / dh (\rho v2 / 2)$$

where
R = pressure loss
λ = friction coefficient
dh = hydraulic diameter (ft)

Duct Sizing Calculations

E1

Notes: Exhaust from 1st Floor special spaces (electrical rooms, bathroom, janitor's closet, and fire pump moved to decrease height requirement on 2nd floor from 18+14=32 to 18". May save some ductwork.

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Room 121	12	1	30	42	24x12	18	2095	1049	0.09	0.0388	
		8	2	45	53	26x14	21	2660	1056	0.08	0.0424	
	1st Floor Corridor	2	1	15	17	14x8	12	565	736	0.08	0.0144	
		17	1	30	47	14x14	15	875	638	0.04	0.0207	
	2nd Floor Corridor	40	1	15	55	24x14	20	2660	1144	0.1	0.0529	
											0.1692	
Adjusted	Room 121	14	2	45	59	14x8	12	565	736	0.08	0.0499	
	1st Floor Corridor	14	0	0	14	24x14	20	1785	763	0.05	0.0064	
		3	1	15	18	14x14	15	875	638	0.04	0.00792	
		22	4	120	142	26x16	21	2660	924	0.06	0.0801	
	2nd Floor Corridor	6	1	30	36	26x16	21	2660	924	0.06	0.0203	
											0.1646	**-0.005**

EB2

Notes: Exhaust from 2nd Floor bookstore spaces moved to decrease height requirement on 2nd floor from 6+18=24 to 6+14=20".

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Room 226	32	1	25	57	18x6	11	425	565	0.06	0.0349	
		8	2	20	28	12x6	9	425	848	0.15	0.0414	
											0.0763	
Adjusted	Room 226	80	2	40	120	20x6	13	425	509	0.05	0.059	
		8	1	30	38	10x6	11	145	356	0.03	0.0128	
											0.0718	**-0.005**

Ceiling needs lowered 10" (9'-6" ceilings)

EB2.1

Notes: Exhaust from 2nd Floor bookstore spaces moved to decrease height requirement on 2nd floor from 6+18=24 to 6+14=20". Will add some ductwork.

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Room 226	54	1	20	74	44x26	36	8650	1088	0.04	0.0309	
		16	3	120	136	44x22	32	6755	1006	0.04	0.0558	
											0.0867	
Adjusted	Room 226	54	1	25	79	56x18	33	8650	1235	0.07	0.052	
		16	3	40	56	48x18	32	6755	1127	0.06	0.0326	
											0.0846	**-0.002**

S3

Notes: Supply to conference corridor adjusted to AHU-6 mechanical room and through kitchen space.
Allows ceiling to be lowered from 12+24=36" to 24" in corridor. Must switch to wall-mounted diffusers.

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Conference Corrido:	12	2	50	62	26x12	19	1325	616	0.03	0.0159	
		22	0	0	22	26x12	19	990	460	0.02	0.0044	
		20	0	0	20	22x10	16	660	430	0.02	0.0044	
		22	0	0	22	14x8	12	330	436	0.03	0.0073	
											0.032	
Adjusted	Conference Corrido:	6	1	15	21	30x12	20	1325	534	0.02	0.0052	
	Room 330	46	4	70	116	30x12	20	990	398	0.01	0.017	
		16	1	25	41	14x14	14	330	249	0.01	0.002	
	Kitchen	12	0	0	12	28x12	20	660	282	0.01	0.00097	
		16	1	25	41	14x14	14	330	249	0.01	0.002	
		32	3	60	92	14x14	14	330	249	0.01	0.0049	
											0.0321	**0.0001**
											negligible	

E3.1

Notes: Exhaust from kitchen (E-40, grease exhaust) moved to align with grease duct at servery and through deleted column.
Allows ceiling to be lowered from 20+24=44" in corridor. Must realign parallel exhaust (E-53) as well.

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Kitchen	6	0	0	6	18x18	18	3200	1422	0.14	0.00849	
	Conference Room	60	2	80	140	32x20	27	5840	1316	0.08	0.11727	
											0.1258	
Adjusted	Kitchen	6	0	0	6	18x18	18	2640	1177	0.1	0.0059	
	Conference Room	38	2	80	118	32x20	27	5840	1316	0.08	0.09885	
											0.1048	**-0.021**

E3.2

Notes: Exhaust from kitchen spaces (E-46) moved to an added space that follows an apartment furnace space to the penthouse for release. Allows ceiling to be lowered from 8+24=32" in corridor. Includes 10x6 EA from room adjoining trunk line.

	Location	*Str. L.*	*Turns*	*Eq. L.*	*Total L.*	*Rect. Size*	*Equiv. Dia.*	*Air Flow*	*Velocity*	*Friction Loss*	*Pressure Drop*	
Existing	Room 342	12	1	15	27	10x6	8	75	203	0.01	0.0034	
	Room 339	3	0	0	3	12x6	8	310	636	0.09	0.0026	
		14	0	0	14	12x6	8	385	763	0.12	0.0171	
	Room 325	3	1	15	18	10x6	8	100	254	0.02	0.0033	
		14	0	0	14	12x6	8	485	975	0.19	0.0267	
	Room 321	10	0	0	10	10x8	8	125	229	0.01	0.0012	
	Room 322	24	1	15	39	10x8	8	235	420	0.04	0.0142	
	Conference Room	18	1	65	83	16x8	12	720	810	0.1	0.079	
											0.1475	
Adjusted	Room 321	10	0	0	10	10x6	8	125	305	0.03	0.00256	
	Room 322	18	1	30	48	10x6	8	235	559	0.08	0.0363	
	Room 324	16	0	0	16	12x6	8	335	678	0.1	0.0158	
	Kitchen	12	0	0	12	12x6	8	435	890	0.16	0.0194	
	Room 342	7	1	15	22	10x6	8	75	203	0.01	0.0027	
	Room 339	4	0	0	4	16x8	12	720	810	0.1	0.0038	
	Dining Servery	16	0	0	16	30x24	29	6560	1314	0.08	0.0121	
											0.0927	**-0.055**

Value Engineering

The cost estimate of the ductwork changes amounts to less than $1,200. As demonstrated in the structural section, the savings of 18” in the overall height of the St. Paul building amounts to approximately $396,000 savings. The costs of instituting a 3-D digital model will be discussed later. Therefore, the rerouting of six branches of ductwork on three floors to lower the height of the plenum produced a cost savings of $394,800 on the St. Paul building.

MEP Value Engineering

15810	Metal Ductwork	Total:	$ (282.30)	lb					
		Crew	Daily Output	Quantity	Unit	Mat	Labor	Equip	Total
	Galvanized Steel	Q-10	$ 285.00	$ (282.30)	lb	$ 0.48	$ 3.31	$ -	$ 3.79
						$ (135.50)	$(934.41)	$ -	$ (1,069.92)
	For Duct Insulation: add 10%								$ (1,176.91)

Existing: **$ 3,753.50**
Adjusted: **$ 4,035.80**
Difference: **$ (282.30)**

The adjusted return air system costs $1,177 more than the existing MEP drawings.

E1

	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Room 121	12	24x12	18	36	7.8	93.6	
		8	26x14	21	40	8.6	68.8	
	1st Floor Corridor	2	14x8	12	22	4.7	9.4	
		17	14x14	15	28	6	102	
	2nd Floor Corridor	40	24x14	20	38	8.2	328	
							601.8	
Adjusted	Room 121	14	14x8	12	22	4.7	65.8	
	1st Floor Corridor	14	24x14	20	38	8.2	114.8	
		3	14x14	15	28	6	18	
		22	26x16	21	42	9	198	
	2nd Floor Corridor	6	26x16	21	42	9	54	
							450.6	**-151**

EB2

	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Room 226	32	18x6	11	24	5.2	166.4	
		8	12x6	9	18	3.9	31.2	
							197.6	
Adjusted	Room 226	80	20x6	13	26	5.6	448	
		8	10x6	11	16	3.4	27.2	
							475.2	**278**

EB2.1

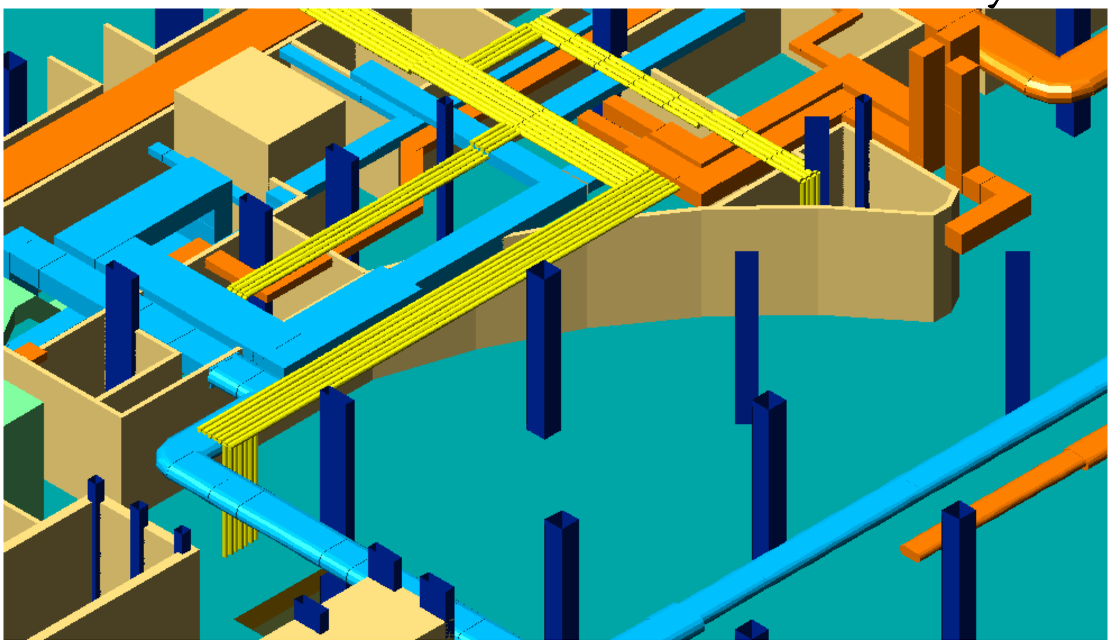
	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Room 226	54	44x26	36	70	17.5	945	
		16	44x22	32	66	16.5	264	
							1209	
Adjusted	Room 226	54	56x18	33	74	18.5	999	
		16	48x18	32	66	16.5	264	
							1263	**54**

	S3							
	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Conference Corridor	12	26x12	19	38	8.2	98.4	
		22	26x12	19	38	8.2	180.4	
		20	22x10	16	32	6.9	138	
		22	14x8	12	22	4.7	103.4	
							520.2	
Adjusted	Conference Corridor	6	30x12	20	42	10.5	63	
	Room 330	46	30x12	20	42	10.5	483	
		16	14x14	14	28	3	48	
	Kitchen	12	28x12	20	40	8.6	103.2	
		16	14x14	14	28	3	48	
		32	14x14	14	28	3	96	
							841.2	**321**

	E3.1							
	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Kitchen	6	18x18	18	36	7.8	46.8	
	Conference Room	60	32x20	27	52	13	780	
							826.8	
Adjusted	Kitchen	6	18x18	18	36	7.8	46.8	
	Conference Room	38	32x20	27	52	13	494	
							540.8	**-286**

	E3.2							
	Location	*Str. L.*	*Rect. Size*	*Equiv. Dia.*	*Sum-2 Sides*	*Lbs/Lf*	*Lbs*	
Existing	Room 342	12	10x6	8	16	3.4	40.8	
	Room 339	3	12x6	8	18	3.9	11.7	
		14	12x6	8	18	3.9	54.6	
	Room 325	3	10x6	8	16	3.4	10.2	
		14	12x6	8	18	3.9	54.6	
	Room 321	10	10x8	8	18	3.9	39	
	Room 322	24	10x8	8	18	3.9	93.6	
	Conference Room	18	16x8	12	24	5.2	93.6	
							398.1	
Adjusted	Room 321	10	10x6	8	16	3.4	34	
	Room 322	18	10x6	8	16	3.4	61.2	
	Room 324	16	12x6	8	18	3.9	62.4	
	Kitchen	12	12x6	8	18	3.9	46.8	
	Room 342	7	10x6	8	16	3.4	23.8	
	Room 339	4	16x8	12	24	5.2	20.8	
	Dining Servery	16	30x24	29	54	13.5	216	
							465	**66.9**

Three-Dimensional MEP Coordination Analysis



Three-Dimensional CAD Background

Three-dimensional digital modeling using CAD programs have been studied at Penn State for many years, although the use of 3-D in the practice is quite sparse. Three-dimensional modeling requires CAD technology that can be a tough investment barrier for many companies, but it has been proven many times that 3-D CAD modeling can pay for itself on each project. Why is it not used more often?

- New technology: As with many new technologies, awareness is the major first-step.
- Lack of 3-D CAD technicians: There are very few programs in the country that surpass the standard 2-D CAD curriculum.
- 3-D CAD Software Deficiencies: Some argue that the current AutoCAD 2006 3-D software does not have enough stream-lined tools for the time-stringent building industry. Which software is best to use for 3D CAD analysis? Will there be better software in 6 months?
- No driving proponent: There are no members of the project team that have a specific investment of interest in this technology: MEP engineers don't want to spend the extra time, MEP subcontractors charge for the service, and most superintendents are practical-minded individuals that can be "computer-challenged." Only the project managers are in the position to "sell" 3-D CAD to the owner and the division manager of their company.

As described by Jessica Potkovick, 2005 Architectural Engineering graduate, there are many benefits of 3-D CAD, which are listed below.

- Higher Quality of Work: CAD makes it easier to explore different results and offers improved accuracy and aesthetics.
- Ability to Eliminate Interferences: Allows you to identify system interferences.
- Personal Development and Achievement of Staff: Implementing CAD technology opens up new positions and provides a challenging environment for staff.
- Better Team Communication: Allows for more efficient collaboration because system is paperless.
- Design Flexibility: CAD offers tools that allow for quick and easy modification of designs.

Deciding whether to use or not use three-dimensional analysis is not a frequented decision amongst the project management staff. It was first implemented by CollinsWoerman, a Seattle-based architectural firm, on the UW Research & Technology project that was discussed in the DBOM/BOT section of this report. The first respondent, Jon Szczesniak, worked on the digital modeling required for the coordination of this high-tech laboratory. The floor-to-floor height was reduced from 15' to 13'-6" as a result of the 3-D digital modeling. The introduction of digital modeling was described by Mr. Szczesniak in the following:

It's important to realize that out here, in Seattle, the idea of digital coordination is fairly fresh. There have only been a handful of projects that have used this to it's fullest capacity. I believe it was Mortenson who had originally brought up the idea of modeling the building in three dimensions for the explicit purpose of coordinating the different trades that were to make up this Research & Tech. building. They have done similar processes on the Disney Concert Hall, and it is becoming their standard way to work with architects and all subs.

The primary purpose of the 3D modeling was for MEP coordination, which began in the middle of the construction document phase. It was Jon Szczeniak's opinion that if the 3D modeling was started earlier, at the beginning of the design development phase, the design could have been coordinated between the professional engineers and not require the added coordination costs incurred by the subcontractors. Nevertheless, Mr. Szczeniak went on to describe the process:

... the design sequence/timeframe was from the CD phase through construction. We got together every other Tuesday and went through the project. Each floor was separated out and coordinated by itself. We used specialized software that would allow us to view the building stereoscopically in real-time so that we could see that when plumbing had a collision with

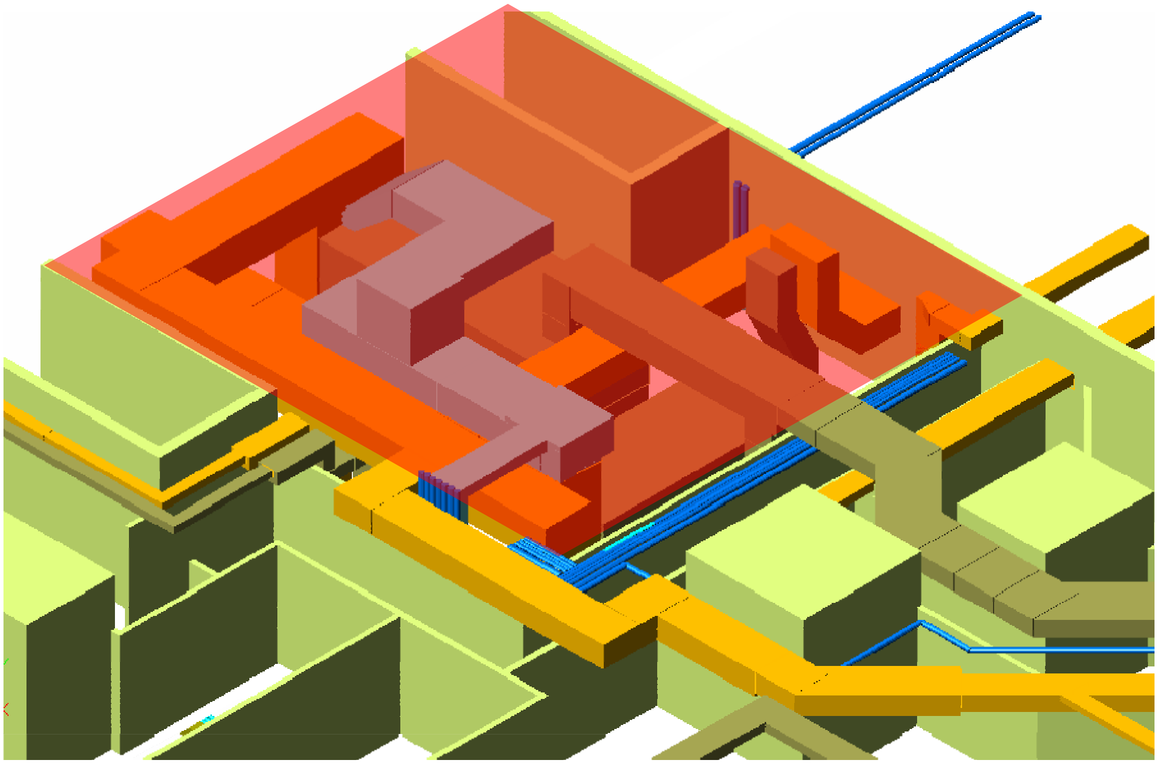
electrical, we could zoom right to it and see how to best resolve the issue. Each coordination meeting had parties from all trades.

Mr. Szczeniak and Mr. Whitlow believed that this MEP coordination process was a success that saved the UW Research & Technology Building in lower building height, construction conflicts, and access issues. Without the project team cooperation that results from a DBOM delivery, the UW Research & Technology Building may not have considered the cost and schedule benefits from 3-D MEP Coordination.

3D Mechanical Rooms

Second Floor Mechanical Room, AHU 4 & 5

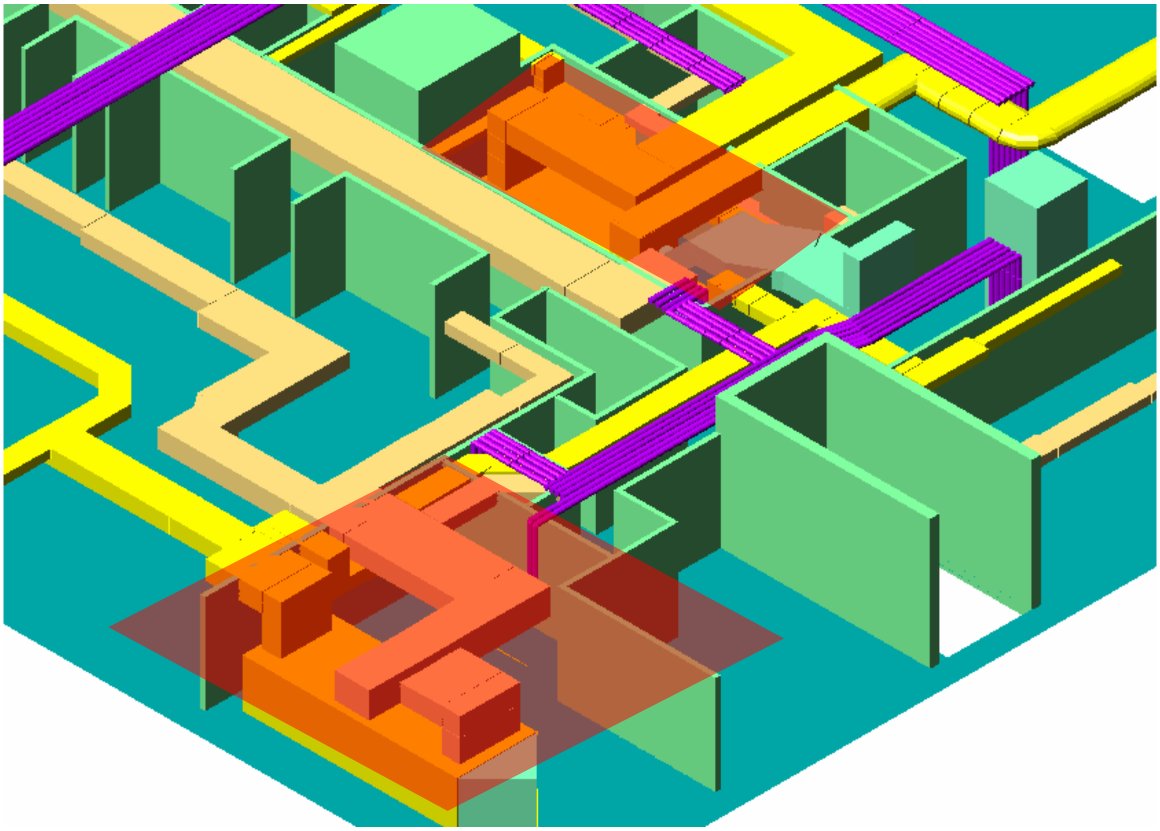
Although the 3-D modeling was very useful for the branch ductwork rerouting, it can be even more integral to the construction of the cramped mechanical rooms. All of the mechanical rooms did not have complete attached ductwork. For example, outdoor air ductwork did not connect with the AHU's, it only terminated inside the mechanical rooms. Two full-size AHU's and a fan-coil unit were squeezed into this space. The blue ductwork (Outdoor Air) is funneled in from the 5^{th} floor courtyard intake. The brown ductwork (Supply Air) supplies the bookstore spaces and the orange ductwork (Return/Exhaust Air) returns to be mixed with the OA. In addition, chilled water from the rooftop chillers cycle to this room and distributes to the 1^{st} floor fan-coil unit.



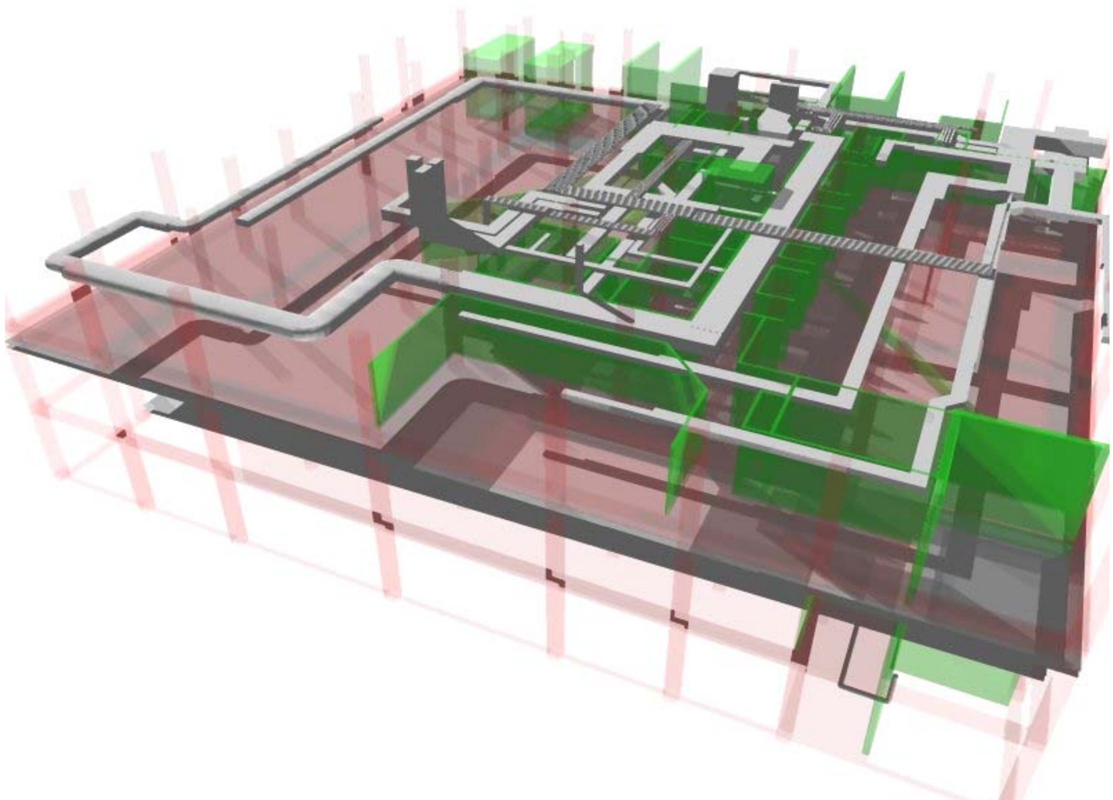
Third Floor Mechanical Rooms, AHU 6 & 7

The nearest mechanical room intakes exhaust air from the 3rd floor intake from Lovegrove St. This AHU supplies (yellow ductwork) the adjacent conference room. The return/exhaust air (tan ductwork) cycles back to the AHU and mixes with the intake OA air, returning to AHU 7.

The smaller mechanical room feeds supply air to the kitchen and dining room spaces and returns air through a small corridor between the mechanical room and the conference room. This return duct is 60"x24" and three of the six ductwork rerouting dealt with adjusting all of the ductwork around it. The purple chilled water piping supplies the AHU's and the kitchen equipment/sinks.



Four-Dimensional MEP Coordination Analysis



Four-Dimensional CAD Background

A few years ago, time was added to three-dimensional CAD, as had been done to photographs to create motion-pictures many decades before. But the quest was different, ticket sales was not the product of the added dimension. Four-dimensional CAD produces the understanding of a 2-D paper schedule combined with a 3-D building model. In all intents and purposes, two and three dimensions should produce five dimensions.

The primary difference between 3-D and 4-D CAD is not time, but its use in the project. 3-D CAD is used best in the design stages, when design professionals are not sure that their design, when constructed, will compete with other systems or not be desirable. 4-D is used for construction managers in the common pursuit of sequencing excellence. Few project managers have the experience to sequence construction with the same talent and sixth-sense ability of the veteran superintendents. However, on extremely-complicated and time-constrained projects, 4-D CAD can help guarantee the project's success. The following are disadvantages of 4-D CAD in addition to 3-D CAD.

- Lack of 4-D CAD equipment: There are very few 3-D labs in the country, due mostly to their very large cost. In addition, offices that already lack space for

their own employees must donate large conference rooms full of equipment for such an endeavor.

- 4-D CAD Software Deficiencies: Not only do technicians need to deal with individual software problems, but the cross-importing that takes place between the 3-D software, schedule software, and the 4-D compiler can be difficult in itself. No single-point software has been developed yet.
- Construction software: 4-D CAD needs 3-D CAD cooperation from the engineers and a compelling urge from the construction side to "go where no one has gone before."
- Two variables: Not only do design changes affect the model, but schedule effects have an excellent chance to disrupt the entire process.
- Superintendent Sequencing Input: 4-D tests superintendent computer skills and patience. 4-D coordination requires too much of the superintendent's time and subcontractor foremen could get confused. Only for the most adventurous superintendents (project managers should not be involved).

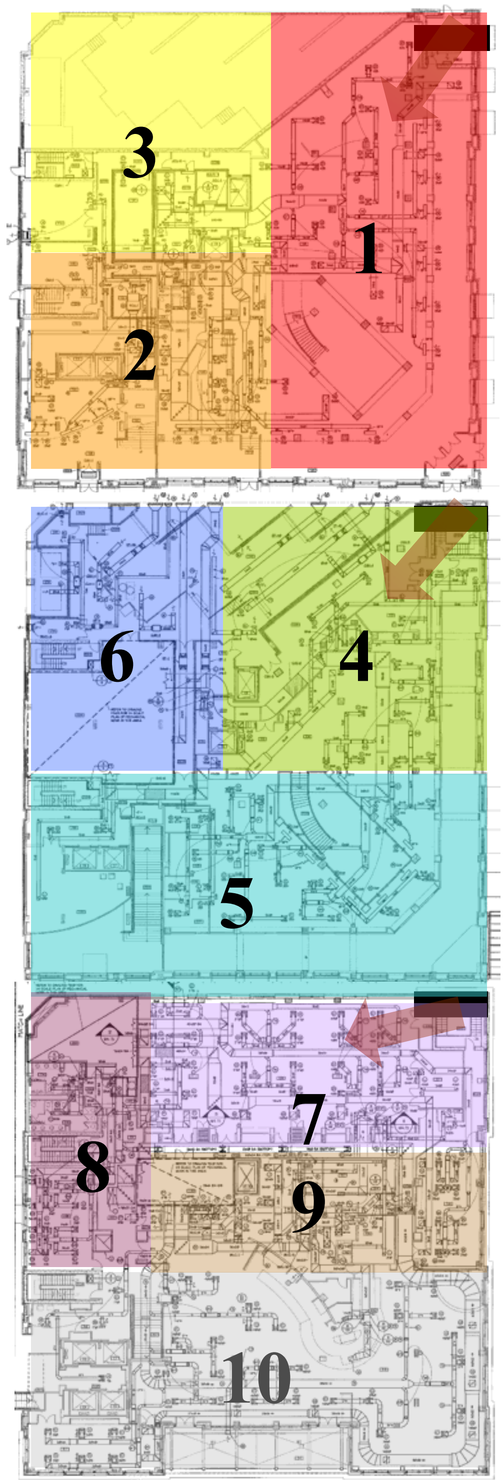
The advantages of 4-D include the advantages of 3-D and the following:

- Looks Cooler: Owners may be entertained by the motion of the pictures.
- Ability to Eliminate Sequence Problems: Allows you to identify system interferences and sequence problems before the system gets placed.

4-D CAD seems to be a tool in the superintendent's toolbox and 3-D CAD seems to be a tool in the project management/design box. On jobs in which more than three superintendents are employed and the building is extraordinarily complicated or large, 4-D may be a good consideration. In addition, more areas are applicable to the 3-D CAD such as structural conflicts, architectural rendering, and more refined interior walkthroughs. 4-D CAD surfaces are dulled down to basic colors in Navisworks to allow the program to work, where 3-D CAD surfaces imported to 4-D Viz can produce realistic architectural walkthroughs.

Constructability Review

The MEP sequencing for the first three floors of St. Paul building are difficult. There are no obvious "typical" bays, no even distributions of systems, and no common layout on each floor. However, each floor has a similar sequence for laydown, secondary spaces, and auxiliary spaces. For example, sequence 1 begins in the area of the bookshelves near the material hoist (northeast arrow) with the CMU block layers so that it is easy to store palettes to begin the production week. Since there is little block to lay in sequence 1, the block-layers can easily move to the next space and stay ahead of the interior partitions. As the interior framing crews get ahead as well, the ductwork rough-in can laydown their sheetmetal and work the branches toward the mechanical equipment. All of the other trades cycle on the heels of the HVAC sheetmetal workers. The last space to complete is the exposed ceiling dining area on the third floor, where care can be taken to maintain the aesthetics of the exposed oval-ductwork.



First Floor Sequence (1-3)

1. Bookshelves – space is expansive to store the 1st floor's load of material by utilizing material hoist (northeast arrow).
2. Lobby – the space is not overcomplicated with ductwork or plumbing, block layers get ahead. Install FCU-1.
3. Auxiliary Rooms – fire pump and electrical rooms are laid out and electrical is fed into the building.

Second Floor Sequence (4-6)

4. Bookshelves – space is expansive to store the 2nd floor's load of material by utilizing material hoist.
5. Lobby – the space is not overcomplicated with ductwork or plumbing, block layers get ahead.
6. Mechanical Room 1 – AHU's 4 & 5 are installed and a myriad of ductwork is installed.

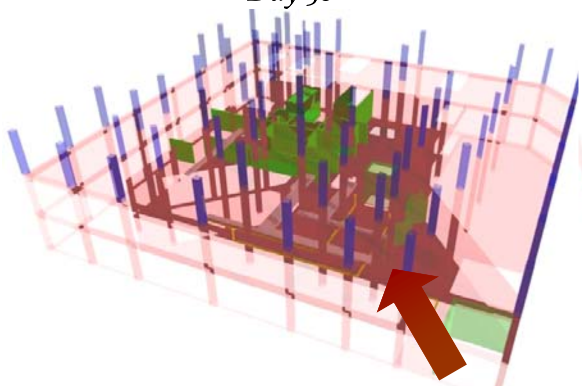
Third Floor Sequence (7-10)

7. Conference Room – space is expansive to store the 3rd floor's load of material by utilizing the material hoist.
8. Mechanical Room 2 – AHU 7 is installed and ductwork is extended to the adjacent mechanical room.
9. Mechanical Room 3 – AHU 6 is installed and the kitchen exhausts and piping is installed.
10. Dining Room – oval ductwork is installed and lighting is positioned.

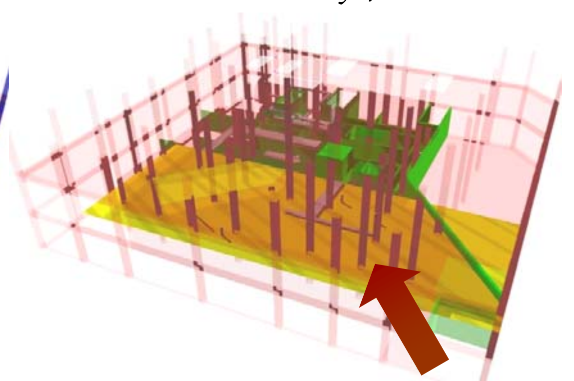
4-D Sequencing Analysis

Designations:
Arrow - flow of materials from the material hoist
Structure - blue columns are in-construction, red columns are completed
MEP - yellow areas are in-construction, grey areas are completed

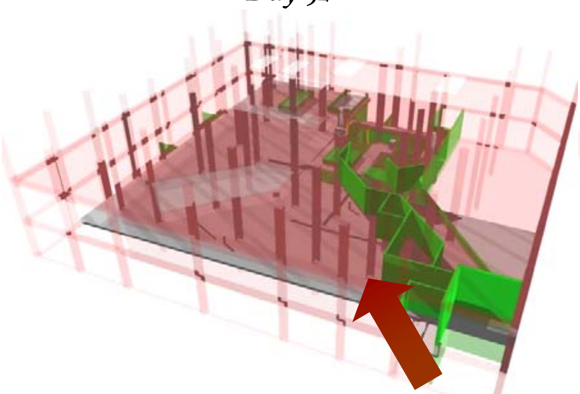
Day 36



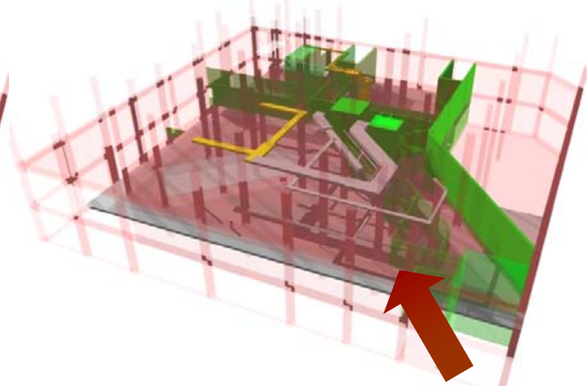
Day 42



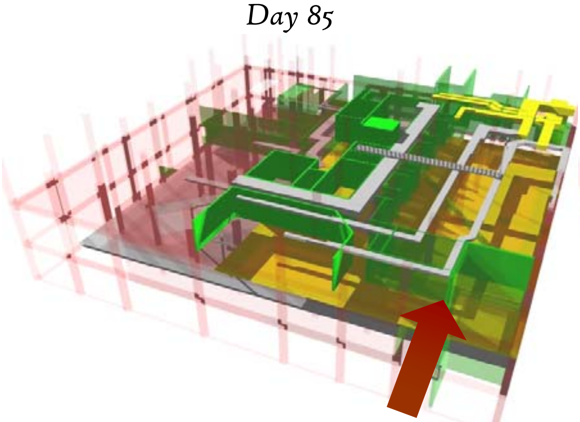
Day 52



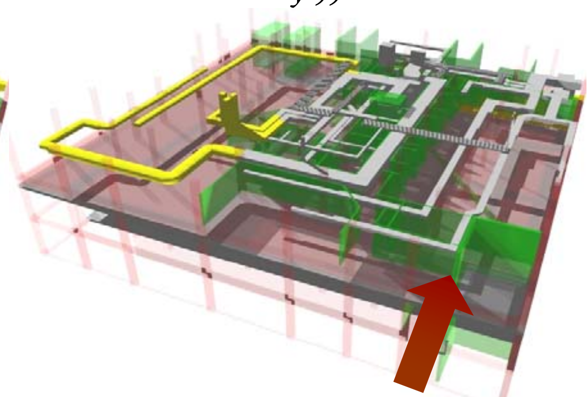
Day 66



Day 85



Day 99



The analysis of the 4-D sequencing using Navisworks showed the inherent complexity of the 10-sequence system I had proposed before. Each area overlaps another area due to the inherent uneven production caused be the "custom" floor plans of the first three floors. Since it was impossible to cut each floor into perfectly manageable sections, the opening floor sequence was designed to allow the other trades to stay ahead of the MEP workers. In many areas, ductwork and plumbing overlap adjacent wall construction and vice versa. This is the single most important limiting factor for 4-D sequencing.

4-D modeling is excellent for equally-divisible and work-intensive spaces such as analyses using SIPS or Short-Interval Production Schedules. Although the apartment spaces in St. Paul and Charles buildings are equally-divisible, the work inside each apartment is not work-intensive. Instead, each of these floors were constructed simultaneously, with multiple crews working all of the floors at once. The first three floors of the St. Paul building bogged down in the non-repetitive work, where the layouts changed constantly and each space was work-intensive in its own way. These two factors are what would constitute an ineffectiveness on the part of 4-D modeling on the St. Paul building.

MEP Coordination Analysis Comparisons

Analysis Method	Time to Complete	Coordination/Sequencing Issues Fixed
2-D	4 hours	6
3-D	24 hours combined	2
4-D	32 hours combined	0

Analysis Method	Advantages	Disadvantages
2-D	Superintendent comprehend fully Universal process No barriers	Difficult to communicate Difficult to analyze height conflicts Low ability to eliminate interferences Little design flexibility
3-D	Higher quality of work Ability to eliminate interferences Personal development and achievement of staff Better team communications Design flexibility	New technology Lack of 3-D CAD technicians 3-D CAD software deficiencies No driving proponent
4-D	Looks cooler Ability to eliminate sequence problems	Lack of 4-D CAD equipment 4-D CAD software deficiencies Construction software Two variables Superintendent sequencing input

Mechanical Conclusion

Three-dimensional digital modeling is the best method to alleviate the MEP coordination issues associated with floors 1-3 of the St. Paul building. The benefits of communicating complicated spaces such as cramped mechanical rooms and adding piece-of-mind such that the ductwork will not conflict with the walls and other systems make the extra 24 hours worth the time. In addition, it is in the project's best interest for the 3-D digital modeling for the MEP systems be performed during the design development stages of the project so that designs provided by the mechanical engineer can be more useful, as done on the UW Research & Technology Building.

Two-dimensional analysis is useful for superintendents and personnel that are using the information for their own job. Communication of a 2-D analysis is very difficult and the drafting of such documents can take longer than that of 4-D digital modeling. In addition, the process requires the user to be able to perceive the height limitations and have a three-dimensional mind.

Four-dimensional models are very convenient constructability analyses tools, but are very difficult to communicate. 4-D modeling helps eliminate sequencing issues on typical sequence structures and work-intensive areas. However, the custom layout of the 1^{st}-3^{rd} floors of the St. Paul building make sequencing accuracy and comprehension more difficult than on other projects.