Final Report: Evaluation of DOAS Paired with Chilled Beams

TEMPLE UNIVERSITY –TYLER SCHOOL OF ART

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TEMPLE UNIVERSITY TYLER SCHOOL OF ART

Building Information

SF	234,000 SF
STORIES	4 (1 SUBFLOOR)
DATE OF CONSTRUCTION	MAY 2007-JANUARY 2009
DELIVERY	DESIGN/BUILD

Design Team

OWNER	TEMPLE UNIVERSITY
ARCHITECT	CARLOS JIMENEZ STUDIO/H2L2 ARCHITECTS & PLANNERS
GENERAL CONTRACTOR	HUNTER ROBERS CONSTRUCTION GROUP
MEP ENGINEER	BRINJAC ENGINEERING
STRUCTURAL ENGINEER	O'DONNELL, NACCARATO, AND MACINTOSH
LIGHTING CONSULTANT	LIGHTING DESIGN COLLARBORATIVE

Architectural
-Signature building of new arts campus
-Divided into subdivisions of adminstration, auditorium, and art education
-Features double height main lobby with glass curtain wall that connects to Presser Hall renovation
-Double height promenade stretches length of building

Mechanical
-HPS supplied from central heating plant
-4 basement AHUs, 3 RTUs, and 1 basment MAU
-2 AHUs & 1 RTU that serve studios are CAV w/ 100% OA
-Other 2 AHUs and RTUs are VAV

Lighting/Electrical
-11 electrical rooms
-Dual source primary 13.2 kV service
-Majority of lighting is fluorescent
-500 kW diesel driven stand-by generator at 480Y/277V

Structural
-Foundation: Cast in place concrete continuous spread footings
-Floor: Cast in place concrete over corrugated steel deck on hot rolled steel framing
-30'x30' bays with W18x35 girders and W16x26 beams
-PVC membrane roofing w/batten

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Executive Summary

The Temple University Tyler School of Art is a unique education building because the large amount of ventilation air required by the system. The mechanical system includes 4 basement air handling units and 3 rooftop units. Three of the units are 100% outdoor air to handle the high loads of the studios and workshops. The current mechanical system uses a joint variable air volume reheat (VAVR) and constant air volume reheat (CAVR) system.

The Tyler School mechanical redesign will focus on the replacement of the airside systems of the building. The primary goal of the Temple University School of Art mechanical redesign is to increase energy savings and energy efficiency while maintaining the existing comfort levels of the spaces.

The redesigned system will use a dedicated outdoor air system (DOAS) coupled with chilled beams. This system allows the sensible and latent loads to be handled separately, which can greatly increase energy savings and efficiency. The DOAS units manage the ventilation loads of the building and boost the efficiency of the system by recovering system energy with the use of an enthalpy wheel. The active chilled beams are located in the spaces that they serve which adds to the ability to control the sensible load of the space.

The redesigned mechanical system produces cost and energy savings. The redesigned Tyler School yields approximately $160,000 per year in energy cost savings. Also, the electricity consumption of the DOAS/chilled beams is decreased by one-third the amount of the existing mechanical system.

The first cost analysis of the two systems shows that the DOAS/chilled design costs more than $1,000,000 more than the existing system. The redesigned system costs much more than the VAV/CAV system because the large number of chilled beams required for the high sensible load spaces. A 20 year life cycle cost analysis was performed to determine if the redesigned system is truly beneficial or if the first cost is too much to justify. The analysis validates the use of the DOAS/chilled beam system with 20 year cost savings of around $800,000. The system energy costs and first costs produce a break even payback of 8.7 years. This proves the effectiveness of the system, but the estimate does not include maintenance costs, which would be higher for the redesigned system because of system unfamiliarity and the maintenance required on individual beams themselves.

The mechanical redesign affects the electrical system. By replacing the mechanical system, some of the electrical wiring was able to be downsized. This downsizing translates to additional cost savings; however, they are smaller in comparison to the mechanical savings.

Despite the complexity of the system and the additional first cost of the system, the redesign system is recommended as an alternative to the current mechanical system. The technology is still not widely used throughout the United States, which boosts the cost, but the energy savings makes it worthwhile.

Project Background

The new 234,000 square foot Temple University Tyler School of Art is a 3-story art education building located in Philadelphia, PA. The Tyler School is moving from its current location in the Philadelphia suburb, Elkins Park. The three floors and basement consist of 234,000 square feet of administration, art education, and auditorium space.

The move from Elkins Park, PA will create a complete Art Campus at the Temple University Main Campus. Architect Carlos Jimenez, known throughout the country for his work on art education buildings, will primarily lead the design team. The goal is to create a "mini arts campus" within the Temple University main campus. The Tyler School will become the signature building of the Arts Campus. As a premier art school of the Mid-Atlantic region, the Tyler School will benefit from the move into one of the largest culturally rich art cities in the country.

The Tyler School of Art building will provide studios, classrooms, shops, assembly spaces, and office space. The new building will house the painting, printmaking, metals, ceramics, sculpture, glass, fibers, and photography departments. The Tyler School of Art will house approximately 120 faculty members and about 800 students. The new building will give 40% more square footage than the Elkins Park campus. The Tyler School will feature 160,000 SF of teaching and learning space. In addition, the exhibition and presentation space will increase by more than 8,000 SF. These gallery and exhibition spaces are highlighted on the first floor to invite the campus and community participation.

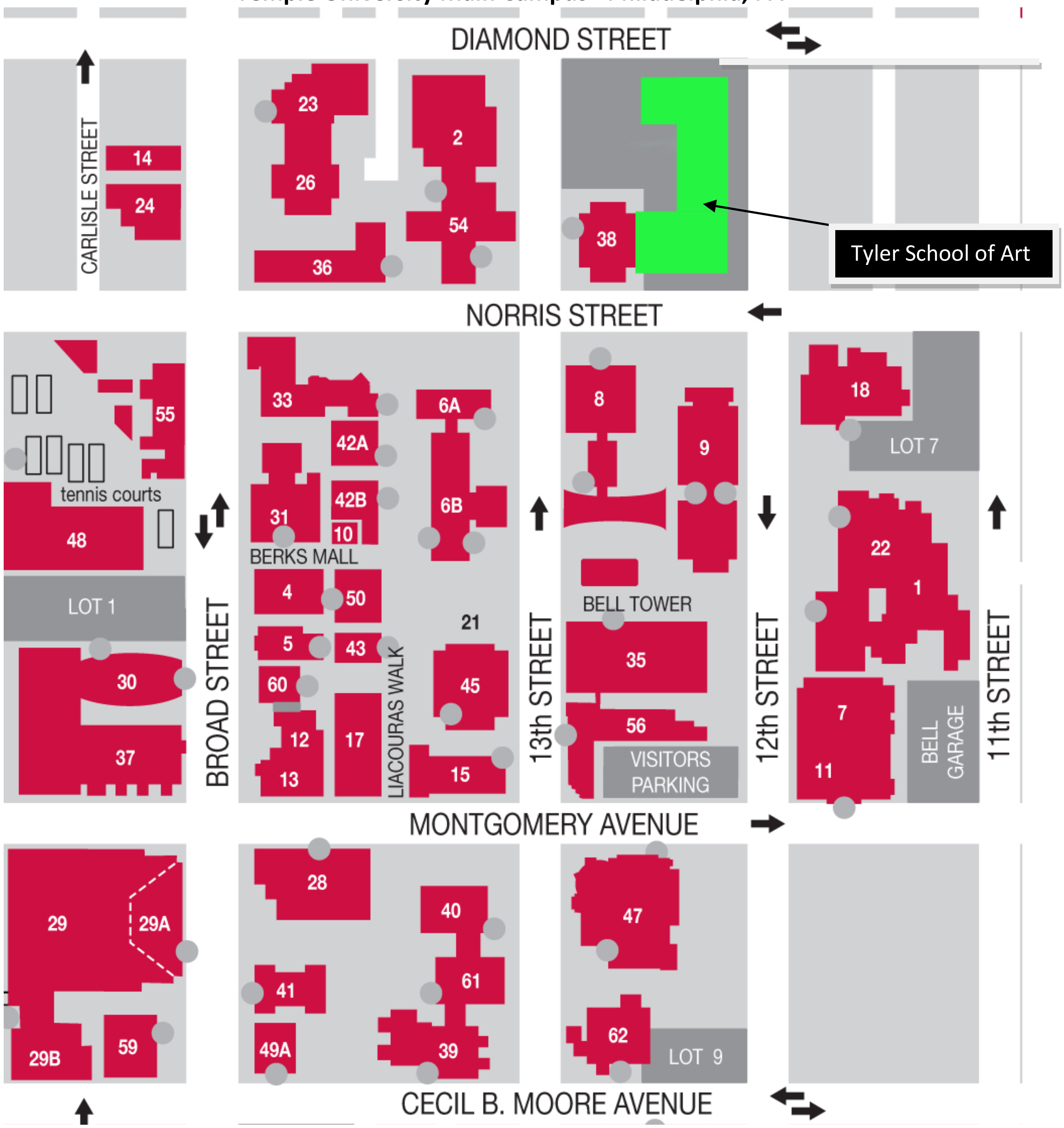
The disciplines in the Tyler School of Art are divided over the three stories and basement. The basement floor is separated into two sections connected by a large mechanical space. The south section is connected to the main lobby by a two-story basement lobby and houses the auditorium and photography studios. The lower level shops are located on the north end of the basement. The 1st floor is broken into zones representing the ceramics, sculpture, and glass departments as well as the school's exhibition space and 1st floor core, which features the main lobby and two-floor promenade that stretches between the two branches of the building. The 2nd floor is broken down into administration and the departments of metals, printmaking, foundations, gaid, and fibers. The painting studios are located on the top floor at the north end of the building.

The Tyler School of Art began construction is currently under construction and will be finished by January 2009.

Tyler School of Art Location

New location of the Tyler School is corner of Norris Street and 12th Street on the Temple University Main Campus.

Temple University Main Campus –Philadelphia, PA



Structural System

The standard foundations are cast in place continuous spread footings and freestanding column footings. Foundation uses cantilevered foundation walls. All of this is done with 4000 psi reinforced concrete. The basement features cast in place reinforced concrete foundations with brick shelves cast in where grade extends below the first floor line. The floor system consists of hot rolled steel framing with and cast in place concrete over the corrugated steel deck. The typical framing grid is 30'x30' with W18x35 girders and W16x26 beams.

Electrical/Lighting System

The Tyler School will receive dual source primary 13.2kV service by using two primary main breakers and a primary tie breaker. The breakers will be electrically interlocked to prevent parallel operation and all the breakers closing at once. The secondary service will use a double ended unit substation. This system will also interlock the breakers in the same manner as the primary configuration.

The substation consists of (2) 600A 15kV high voltage switch compartments, (2) 2,500 kVA 13.2kV Primary 480Y/277V secondary 3-phase 4-wire dry type transformers, (2) 4,000 A circuit breaker main compartments and (1) 4,000 A circuit breaker tie compartment, and six distribution feeder breaker compartments. Eleven electrical rooms will handle the secondary electrical distribution.

The emergency power will be provided by a 500 kW, 480Y/277 Volt, 3-phase, 4-wire, 60 Hz, diesel driven standby emergency generator.

The majority of the lighting will be fluorescent. Specialty lighting is applied to the interior public gathering spaces and the elevator lobbies. The exterior lighting will be time controlled featuring multiple lighting contactors for switching 277V and 120V lighting loads on and off. The exterior areas that are a part of the Tyler School's lighting plan are exterior entrances and exits as well as public and service pathways.

Fire Protection

The fire protection system will consist of an electric motor driven fire pump assembly, with an automatic wet-pipe sprinkler system throughout the building. The wet-piped system will be zoned by floor. There also includes an automatic dry-pipe sprinkler system in areas subject to freezing. The fire rating on the structural frame, bearing walls, and floor construction have a 2 hour rating. The roof construction will have a rating of 1 hour.

An intelligent analog fire alarm system features the standard alarm notification and ADA visual alarm notification. The main fire alarm system panel is located inside the main entry. All strobe lights are wall mounted and use 24V DC synchronized Xenon lamps. All audible notification devices have a minimum rating of 70db. The alarm system has a battery backup that can operate eight hours in standby and ten minutes of full alarm action.

Plumbing

All installation is done in accordance with the Philadelphia Plumbing Code. Domestic water is provided by an existing public water main service entrance. Fire water service to the Tyler School will be provided by a separate water service connected to a fire pump. All piping that is 6-inch or larger is constructed of ductile iron. All piping 4-inch and smaller is copper. All the copper piping is type L hard copper with wrought fittings and solder joints. The sanitary piping is constructed of cast iron.

Transportation

The primary means of transportation for the Tyler School are two passenger elevators that use an undercab hydraulic piston system and are rated at 2,500 pounds each. The one elevator is located on the south side of the building in the main lobby. The other passenger elevator and the freight elevator are both located on the north lobby of the building and extend from the basement to the 3rd floor. There is also a freight elevator using the same system that is rated at 15,000 pounds. At these two lobby locations there are open stairwells in addition to the elevators. There are two egress stairwells on the north side and one near the main lobby because the main stairwells are exposed for multiple floors.

Site Factors

The Temple University Tyler School of Art had many design considerations to take into account. The building is only predominantly 2 stories with a third story housing the painting studio. Despite the massive amount of space needed to house the different departments in the school, the building height was limited to 64 feet high to fit the Temple University master plan.

The large footprint required for the building can cause problems for a dense urban campus, especially because the Tyler School of Art footprint uses an entire city block. This size also creates a problem for the location of entrances and loading docks. The loading dock location was a very important consideration because all departments would need to have easy access to it. A building as large as the Tyler School has several large shipments coming into the school daily.

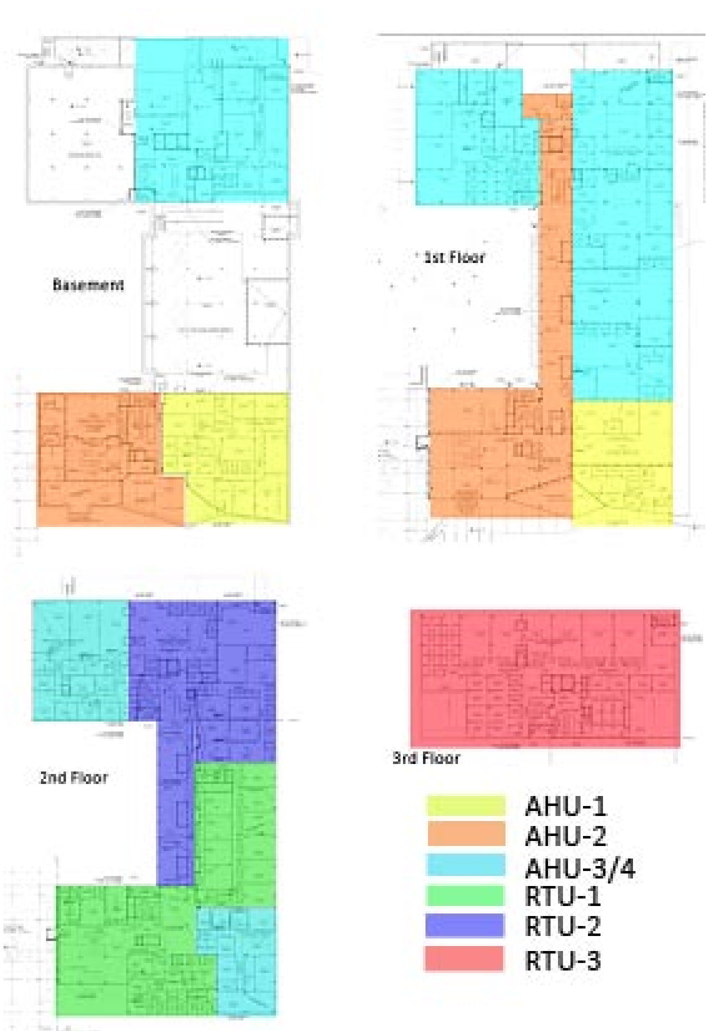
The outdoor intakes were also important site locations. They were located on the courtyard the school is based around. This assures clean intake air away from city car exhaust. The exhaust also had to be considered. Because the building is relatively low, it is required for the roof mounted exhaust fans to project up into the atmosphere so it does not get recirculated into the building or another building.

Mechanical Systems Overview

The Tyler School of Art is a unique education building because the excessive amount of ventilation required. The building was treated primarily as a laboratory. The system consists of four (4) air handling units (AHU) housed in the basement and three (3) rooftop units (RTU). Of the seven units, AHU-1, AHU-2, RTU-1, and RTU-2 are all variable air volume reheat (VAVR) systems. The remaining units, RTU-3, AHU-3, and AHU-4, are all constant air volume reheat (CAVR) systems. These units predominantly serve the studios spaces and shops.

Space	HVAC System
Administration & Office	Variable Air Volume Reheat (VAVR)
Classroom Spaces	Variable Air Volume Reheat (VAVR)
Conference & Presentation	Variable Air Volume Reheat (VAVR)
Workshop & Studio Areas	Constant Air Volume Reheat (CAVR)

The graphic shows the floor breakdown of the AHUs and RTUs.



The building taps into the campus steam lines. High pressure steam is supplied from the Temple University central heating plant. The high pressure steam is brought in at 240°F. The steam is brought to the building and then steam-to-water heat exchangers convert it to hot water. This hot water is then sent through the building to be used in the domestic hot water system as well as the reheat coils, unit heaters, air handling units, and for the steam in the humidifiers. Steam provides the humidification in the Tyler School.

The water is circulated throughout the building by the use of four variable speed drive end suction pumps. The hot water supply is designed at 180 °F and the hot water return is 160 °F. Hot water reset is used to adjust the temperature of the supply water as the ambient conditions vary. Temperature control valves are used to mix the supply and returns lines to adjust to lower hot water supply temperatures.

The chilled water is taken from the Temple University central plant. The chilled water distribution is handled by four variable speed drive, vertical split-case pumps. There is also a standby pump. The pumping arrangement is a secondary pump system that delivers chilled water to the air handling units and uses direct return with two-way control valves. The chilled water system is designed to have a supply temperature of 48°F and return is 60°F.

The building features a large variety of departments that require considerable amount of exhaust in the studios and workshops. To handle this exhaust, additional ventilation is required which greatly increases the load of the building. The Tyler School of Art does not use any energy recovery technology because much of the exhaust is not centralized. The layout of the departments and the additional cost for energy recovery was not seen as beneficial by the university. There is an opportunity to recover the energy the Tyler School by the use of the enthalpy wheel technology available. Different energy recovery configurations will be considered further as well.

Indoor & Outdoor Design Conditions

The outdoor design conditions in the table below for the Tyler School of Art were taken from the ASHRAE Fundamentals 2001 for Philadelphia, PA.

WEATHER CRITERIA		
SUMMER	Dry Bulb	89 F
	Wet Bulb	74 F
WINTER	Dry Bulb	11 F

The indoor design conditions were compiled by Brinjac Engineering and Temple University personnel. The tables in Appendix A summarize the indoor design conditions that correspond with the different occupancy types.

ASHRAE Standard 62.1 Ventilation Compliance

The ventilation systems of the Tyler School of Art were evaluated for compliance with ASHRAE Standard 62.1 *Ventilation for Acceptable Indoor Air Quality*. The evaluation procedure for the ASHRAE Standard 62.1 is based on floor areas, space type, occupancy, and the ventilation system. The procedure calculates the amount of outdoor air required for each AHU/RTU intake to ensure that the various spaces receive the minimum amount of outdoor air required. The design outdoor air percentages as well as the ventilation rates and compliance are summarized in the tables below.

	Supply Max	Outdoor Air	% OA
AHU-1	50,000	16,500	33
AHU-2	50,000	16,500	33
AHU-3/4	124,000	124,000	100
RTU-1	42,000	14,000	33
RTU-2	51,000	14,000	27.5
RTU-3	35,000	35,000	100
MAU-1	5,000	----	----

	Location	Areas Served	Calc. OA (CFM)	OA Min (CFM)	Supply Min	Supply Max	Complies w/62.1
AHU-1	Basement	Photo, Exhibit	12,670	13,500	26,000	50,000	Yes
AHU-2	Basement	LL/1st Floor Core	20,130	13,500	26,000	50,000	No
AHU-3/4	Basement	Ceramics, Sculp, Glass, Metals, Printmaking, LL Shops	23,200	124000	124,000	124,000	Yes
RTU-1	Roof	2nd Flr Admin/Core, Foundations	17,990	21,000	24,750	42,000	Yes
RTU-2	Roof	Gaid, Fibers, 2nd Flr Core	25,325	14,000	28,000	51,000	No
RTU-3	Roof	Painting	13,330	35,000	31,150	35,000	Yes

The tables show that AHU-2 and RTU-2 do not comply with ASHRAE Standard 62.1 2007. These two units do not comply primarily because of design discrepancies for a few of the spaces. These spaces were possibly overdesigned to account for the large amounts of exhaust that is required in many of the studio/workshop spaces.

ASHRAE Standard 90.1 Compliance

ASHRAE Standard 90.1 is the energy standard for evaluating buildings by providing minimum conditions for energy efficient building design. Under this standard, the building envelope, HVAC systems, service water heating, power, lighting, and electric motor efficiency are all evaluated for compliance.

Building Envelope

ASHRAE Standard 90.1 Section 5 specifies the requirements for the building envelope. There are two methods to determine the building envelope compliance. The two methods are the Prescriptive Building Envelope Method and the Building Envelope Tradeoff option. To use the first option the vertical fenestration must not exceed 50% of the wall area and the skylight fenestration must not exceed 5% of the roof area. The total vertical fenestration is less than 30% of the wall area as specified by the design summary. The skylight fenestration area is less than 2% of the total roof area as shown in the table below. Therefore, the Prescriptive Building Envelope Method can be used.

Total Glass Area	Total Roof Area	% Glass
1320	80468	1.64

The Temple University Tyler School of Art is located in Philadelphia, PA which is classified as climate zone 4A from Table B-1 in Appendix B of Standard 90.1. The building is also categorized as now residential. For this classification, Table 5.5-4 is used to determine the minimum R-Values required.

Building Envelope Compliance

	Roof (Insulation Entirely Above Deck) Minimum R-Value		Walls (Metal Building) Minimum R-Value	
Required (90.1)	R-15 Continuous Insulation		R-13	
Actual	4" Thick	R-15 Continuous	6" Thick	R-19
Complies	Yes		Yes	

Vertical Fenestration Compliance

% Glazing (20-30%)	Assembly Max U-Value (Fixed)	Assembly Max SHGC (All Orientations)
Required (90.1)	0.57	0.39
Actual	0.5	0.39
Complies	Yes	Yes

Skylight Fenestration Compliance

With Curb, Glass	Assembly Max U-Value (Fixed)	Assembly Max SHGC (All Orientations)
Required (90.1)	1.17	0.49
Actual	1.0	0.43
Complies	Yes	Yes

HVAC Systems

Section 6 of ASHRAE Standard 90.1 focuses on the mechanical equipment and systems of the building. The Simplified Approach cannot be used for compliance because the building is more than two stories and more than 25,000 SF. Therefore, the Tyler School must be evaluated in regard to the Mandatory Provisions and Prescriptive Path.

The fans used in RTU-3 and AHU-3/4 fail the energy recovery section of 90.1. It is required that fans with capacity more than 5,000 cfm and more than 70% OA must use energy recovery with at least 50% recovery effectiveness. These systems are 100% OA but they use no energy recovery because of the additional cost.

The exhaust fume hoods were tested for compliance with 90.1. The Standard specifies additional consideration for exhaust rates greater than 15,000 cfm. This occurs in the ceramics, Metals/Smithing/Casting/, and Sculpture areas. The Standard requires heat recovery to precondition makeup air, variable air volume exhaust, or a makeup air supply equal to at least 75% of the exhaust rate. These three spaces violate this section.

The Tyler School falls into the climate zone 4a so an economizer is not required in the building. This satisfies one of the requirements under the Prescriptive Path section of section 6 ASHRAE Standard 90.1. There is also no minimum duct insulation R-Value required by section 6 of the Standard.

The gas fired, steam boilers used at the boiler plant must have an efficiency of 83% as per the project specifications. Table 6.8.1F of the ASHRAE Standard 90.1 requires an efficiency of 80%, so this boiler meets compliance.

The chillers come from the Temple University Central Chiller plants. The Tyler School of Art will only be using a small portion of the load created at this plant. The COP and NPLV of each system component are not available, because the chiller plant is being renovated as part of a separate project. The load of the chiller will be >300 Tons and the entering and leaving design temperatures are known, but the exact input and output of the chiller is still being determined.

Compliance for Table 6.8.3 Minimum Pipe Insulation Thickness from Standard 90.1 are below:

Minimum Pipe Insulation

Chiller Water Piping

	Design Operating Temp (F)	Nominal Pipe Size (in.)				
		<1	1 to <1-1/2	1-1/2 to <4	4 to <8	>8
Required	40-60	0.5	0.5	1	1	1
Actual		1-1/2	1-1/2	1-1/2	1-1/2	1-1/2
Complies		Yes	Yes	Yes	Yes	Yes
Required	<40	0.5	1	1	1	1
Actual		1-1/2	1-1/2	1-1/2	1-1/2	1-1/2
Complies		Yes	Yes	Yes	Yes	Yes

Hot Water Piping

	Design Operating Temp (F)	Nominal Pipe Size (in.)				
		<1	1 to <1-1/2	1-1/2 to <4	4 to <8	>8
Required	140-200	1	1	1	1-1/2	1-1/2
Actual		1-1/2	1-1/2	1-1/2	1-1/2	1-1/2
Complies		Yes	Yes	Yes	Yes	Yes

Service Water Heating

ASHRAE Standard 90.1 Section 7 outlines the performance requirements for the service water heating systems and equipment. The performance requirements for water heating equipment are summarized in Table 7.8 of the Standard. The boiler used from the central plant has an efficiency of 83%. These calculations prove that the Tyler School complies with the service water heating section of ASHRAE Standard 90.1.

Power

Section 8 of ASHRAE Standard 90.1 refers to all the power distribution systems within the Tyler School. The standard states maximum requirements for voltage drops of feeders and branch circuits. The Tyler School of Art was designed to meet these requirements and thus complies with ASHRAE Std 90.1-2004.

Feeder has a maximum voltage drop of 2% of the design load.

Branch circuits have a maximum voltage drop of 3% of the design load.

Lighting

Section 9 of ASHRAE Standard 90.1 focuses on the interior and exterior lighting of the building. The two methods to test for compliance are the Building Area Method and the Space-By-Space method. The Building Area Method was used in the calculation for this report. To do so, the following procedure was followed:

- The building types were determined from Table 9.5.1 of the Standard. The Tyler School of Art falls into the categories of school/university, workshops, and office.
- The gross lighted floor area is determined for each building type.
- The interior lighting power allowance is the gross area is multiplied by the power density.
- This figure is compared to the installed interior lighting power, which is the actual wattage in the building, totaled from plans/schedules. The interior lighting power allowance must be less than the installed interior lighting power.

The lighting compliance is summarized in this table:

Space	Area	STD 90.1 W/ft2	Allowable Watts	Total Watts	Complies w/ 90.1
School/University	203,690	1.2	244428	205322	Yes

Existing Mechanical Systems

The Carrier HAP program is used as the building energy simulation program in order to estimate the design loads, annual energy consumption, and operating cost for the Tyler School of Art. The energy simulation is based on the lighting, occupancy, and equipment loads as well as outdoor air ventilation rates.

The table below shows the calculated tons for each unit and the area per ton.

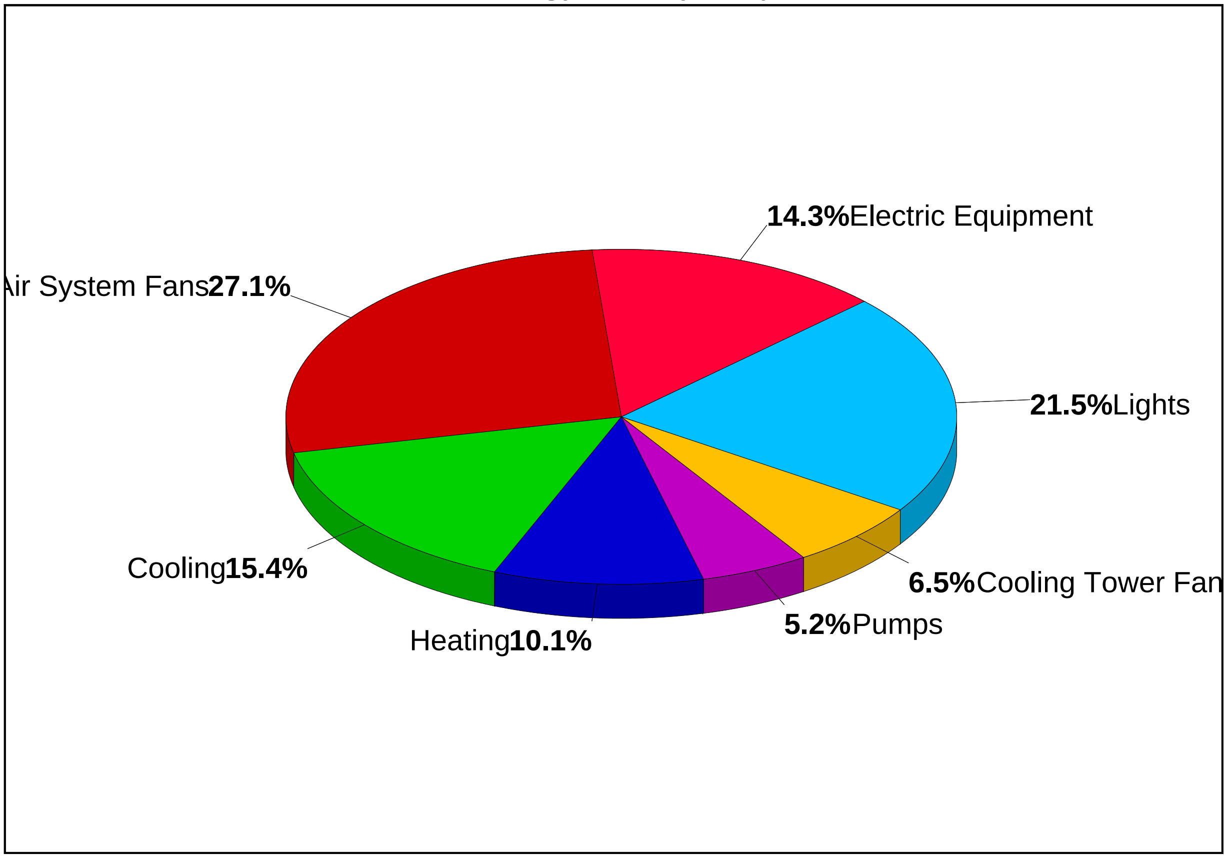
	Tons	Ft^2/Ton
AHU-1/2	213.7	186.2
AHU-3/4	329.2	204.5
RTU-1	210.1	146.4
RTU-2	94.7	229.6
RTU-3	108.8	187.7

The table below shows the design loads for the Tyler School as determined by Brinjac Engineering through the use of Trane Trace. The values correspond well with the loads calculated above.

	Occupancy	Area (SF)	Airflow (cfm)	Sensible (Btuh)	Latent (Btuh)	Total (Btuh)
RTU - 1	Administration	5,671	6,995	179,333	60,659	239,992
	2nd Floor Core	15,953	52,602	1,063,605	167,251	1,230,856
	Foundations	10,883	10,343	471,707	283,536	755,243
		Total CFM =	**69,940**		**Total (Tons) =**	**186**
RTU - 2	2nd Floor Core	2,242	714	41,270	19,291	60,561
	Gaid	10,991	11,667	420,804	176,796	597,600
	Fibers	6,200	4,008	145,828	98,150	243,978
		Total CFM =	**16389**		**Total (Tons) =**	**75**
AHU - 1/2	Lower Level Core	10,656	15,963	540,884	381,607	922,491
	Photography	12,234	7,275	282,491	187,100	469,591
	Exhibitions	8,542	9,155	289,436	237,295	526,731
	1st Floor Core	9,330	6,494	277,992	149,455	427,447
		Total CFM =	**38887**		**Total (Tons) =**	**196**
AHU - 3/4	Sculpture (LL)	10,701	7,405	276,602	175,198	451,800
	Glass	10,626	8,212	347,434	237,662	585,096
	Sculpture (1st Flr)	14,933	15,143	625,820	364,966	990,786
	Ceramics	11,325	14,911	470,148	329,362	799,510
	Metals	7,196	7,226	254,944	120,830	375,774
	Printmaking	11,542	13,658	438,070	226,560	664,630
		Total CFM =	**66555**		**Total (Tons) =**	**322**

The graphic below helps to illustrate the breakdown of the energy costs. As expected for a system with a great deal of outdoor air ventilation, the air system fans make up a large part of this percentage. The heating system is slightly smaller than it should be. As a rule of thumb, the heating should fall in the range of 20-60 Btu/hr, but because this is treated more like a laboratory it should be on the high side of this range. The heating component is only producing approximately 20 Btu/hr.

Annual Energy Costs by Component



VAV/CAV System

One of the main advantages of the VAV system is the low energy cost. The terminal units meet the minimum comfort levels in the room as required by ASHRAE Standards, which leads to low energy consumption and cost. Also, the ductwork and central air handling equipment can be sized down because the diversity factor can be used. The diversity factor is used because it is assumed that the maximum loads do not occur simultaneously. This is ideal because the VAVR system is used in spaces with varying usage like the workshops and studios, which could have varying numbers of people in them at all times.

The energy savings from being able to design for the minimum conditions is a positive, but as a negative, the spaces can seem like there is inadequate air movement. This can be a significant problem in terms of indoor air quality and occupant comfort. The stagnant air can cause the occupants of the space to feel uncomfortable, which can ultimately affect the productivity of the worker. Also, several spaces have to be served by a single terminal unit, which can create balancing problems with adjacent dissimilar spaces.

VAV REHEAT SUMMARY	
Advantages	*Disadvantages*
Low Energy Costs	Inadequate Airflow
Low Maintenance	Single Box Serving Multiple Spaces
Provides Minimum Airflow Required	Air Dumping at Minimum Airflow
Central Equipment	Increased Energy Consumption with Cooling and Reheating
Inexpensive Temperature Controls	Requires Diffusers with Effective Air Distribution
Flexibility	

The CAVR system works similarly to the VAVR system except there is a constant amount of airflow being provided for the space. There are large ventilation requirements, especially in the studios/workshops, which have a great amount of exhaust. Once again, this ventilation will require the reheat coil to allow for system temperature balancing.

The CAVR system is beneficial because it can offer a very low first cost compared to other all-airside systems. Along with this initial cost benefit, this system offers the benefit of the simplest temperature controls. However, these saving are offset by high energy consumption, larger ductwork, and often significant airflow reheating to meet the temperature set points of the rooms. The high-energy consumption is the result of the unit being designed to meet to the sum of all the peak space loads.

CAV REHEAT	
Advantages	*Disadvantages*
Lowest First Cost	High Energy Consumption
Low Maintenance	Large Ductwork
Simple Temperature Controls	Significant Reheat May Be Required

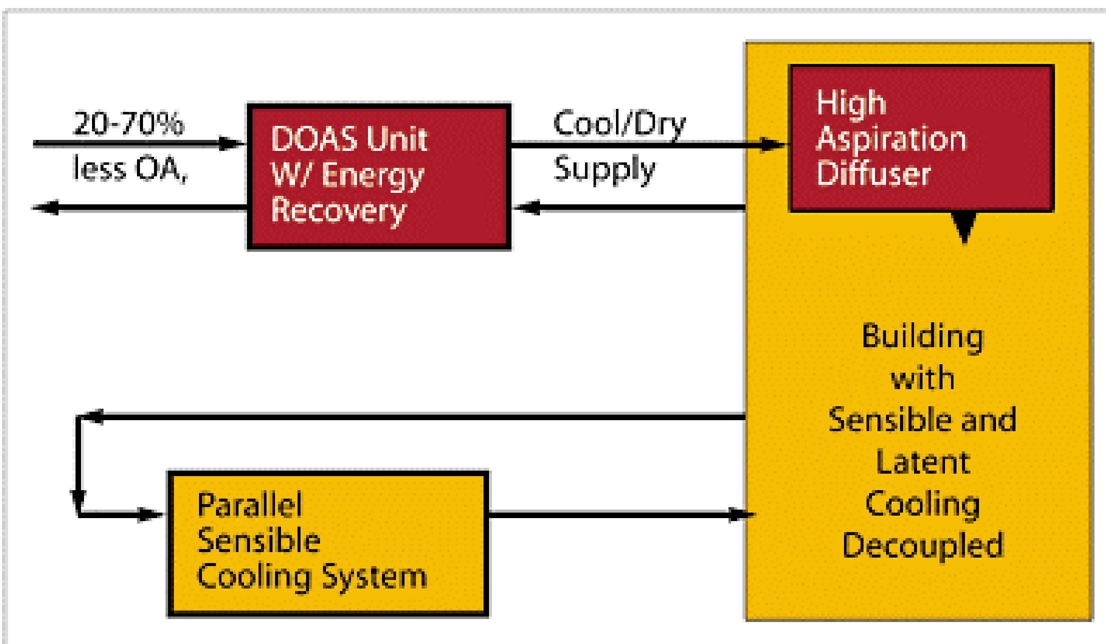
Mechanical System Redesign

Objective:

The main goal of the mechanical systems redesign for the Temple University Tyler School of Art is to improve the energy costs and energy consumption of the building. This redesign does not insinuate a flawed original design, but rather is another way of considering the mechanical design.

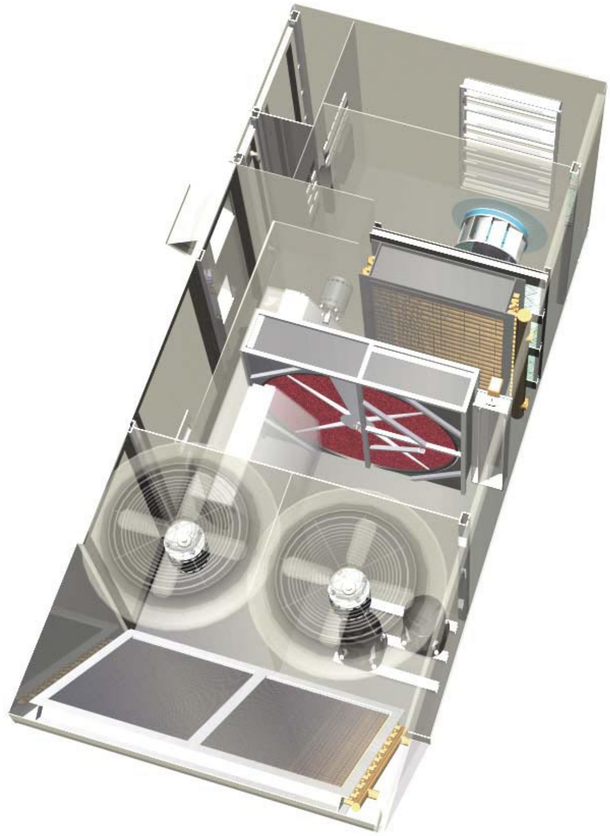
The use of a dedicated outdoor air system (DOAS) with energy recovery paired with a parallel system to handle the sensible load should meet these goals. The parallel system will be active chilled beams. Case studies have shown that the use of DOAS can produce energy reductions of approximately 10% for heating and 17% for cooling by separating the latent and sensible loads. DOAS can be very effective in applications with large amounts of spaces with varying occupancy. The large amounts of outdoor air required by the Tyler School ventilation systems also makes DOAS a very viable alternative.

DOAS paired with energy recovery as well as chilled beams are explained further below. The basic operation of DOAS with the parallel sensible system, chilled beams can be seen in the graphic below.



DOAS

In order to improve the redesign goals the VAVR system will be redesigned as a dedicated outdoor air system (DOAS). A DOAS offers many advantages associated with building ventilation. The primary advantage of DOAS is the lower ventilation that translates to energy savings. Variable air volume (VAV) systems require a high minimum amount of airflow and the VAV system does not supply the proper ventilation air quantities when the VAV box has to serve multiple spaces. The VAV box is sized based on the ventilation requirements in the room and a percentage of the ventilation air in the supply air. If the possible need for reheat in the VAV box is considered as well, the wasted energy load becomes even higher. The higher ventilation requirements coupled with the need to reheat this extra air justifies the consideration of DOAS.



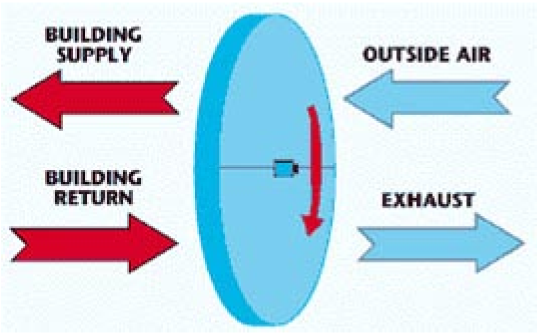
Interior View of Typical Dedicated Outdoor Air System

The use of DOAS separates the sensible and latent loads. DOAS handles the latent load and some of the sensible load. However, DOAS needs to be coupled with a system to handle the rest of the sensible load. The ability to separate these two loads is a great advantage in mechanical system design optimization. The main reason for the loads to be separated is the ability to avoid high relative humidity in the space at low sensible loads. The humidity issues leads to moisture problems which affect the overall indoor air quality of the space. Traditional systems, especially in humid climates, have difficulty balancing ventilation requirements with the humidity. The large ventilation and occupancy load requirements pulls in direct outdoor air. To balance the humidity the system operates at lower supply air than is required by ASHRAE Standard 62.1. This, in turn, affects the indoor air quality of the space because it does not properly ventilate. By changing from the VAV system, the thermal comfort and indoor air quality problems can be alleviated. The improvement of these areas can be invaluable, because they have a strong correlation between productivity and absenteeism.

The Temple University Tyler School of Art has very high ventilation loads to handle the exhaust systems in the studios and laboratories. The use of DOAS with a parallel sensible system can lower this ventilation load greatly by separating the sensible and latent loads. Traditionally, most energy savings associated with the use of DOAS are seen in fan energy and chiller energy use. Studies have shown that the use of DOAS with a parallel sensible system can reduce the energy costs by as much as 30% of a traditional system. The substantial chiller use savings that the DOAS mechanical redesign offer can be important because it limits the load on the Temple University district chiller plant.

Energy Recovery

Various energy recovery configurations were considered. The three most common systems that will be evaluated for the Tyler School are enthalpy wheels, flat-plate heat exchangers, and refrigerant filled heat pipes. The heat exchanger is the most reliable system because it is a passive system. It usually transfers only sensible heat energy (temperature only) back into the outdoor supply air. For the system to work effectively, the temperature and humidity must be comparable to the treated space, and the exhaust airflow rate must be similar to the outdoor air flow rate entering the system.



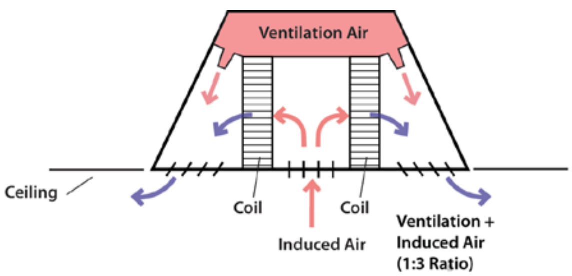
Operation of an Enthalpy Wheel

The enthalpy wheel or energy wheel rotates, mixing the sensible heat energy as well as the humidity with the outdoor air. They are more complex than heat exchangers because the mass and heat transfer are paired together. It is referred to as an enthalpy wheel because of its ability to transfer both heat and humidity into the supply side by the use of a desiccant coating. Enthalpy wheels are usually used for high humidity climates and large ventilation systems, which makes it very applicable to the Tyler School of Art. For this analysis, enthalpy wheels will be used as a component of the DOAS systems. The use of enthalpy wheels as a part of a DOAS will increase the fan energy. This is offset by the cooling and heating load savings in the peak months. Also, the use of the parallel system greatly decreases the fan energy, so the ERV fan increase should not be a factor. The basic principles behind an enthalpy wheel are shown on the right. The advantages and disadvantages of enthalpy wheels are summarized below.

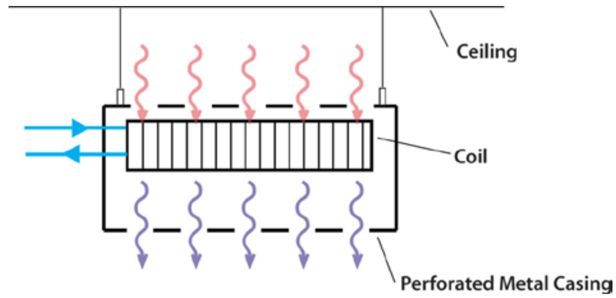
Potential Advantages	***Disadvantages***
Improved Indoor Air Quality	Maintenance Complexity
Reduced Cooling and Heating Loads	Increased First Cost
Humidity Control in Ventilation Air	Increased Fan Energy
Downsize Equipment/Ductwork	Required Air Filtration

Chilled Beams

Chilled beams and radiant ceiling panels are two technologies that efficiently can be coupled with the DOAS and handle the sensible load of the building. The chilled beams will be the technology considered for its application in the Tyler School of Art. Chilled beam technology has been common place in Europe for quite some time; however, just recently the technology has increased in popularity here. The system offers energy savings and reductions in mechanical equipment and duct. Chilled beams can be a passive or active mechanical system. Active systems are connected to the supply air ductwork. The active chilled beams mix the supply air and the existing air that has been cooled. The passive system uses natural convection to cool the space. The warm air rises naturally into the system, which cools the air and then the air falls. The figure below shows the difference the active and passive systems.



Active Chilled Beam



Passive Chilled Beam

Specifically, chilled beams offer a variety of advantages that are summarized in the table below.

Potential Advantages	Disadvantages
Mechanical System and Duct Reductions	Noise
Reduced or Eliminated Reheat	Coordination w/ Lighting Equipment
Pump Energy Instead of Fan Energy	Rooms w/High Loads
Fit in Tight Space	Condensation
Free Cooling and Improved Chiller Efficiency	Cost

The use of chilled beams with DOAS has been proven to reduce the energy consumption of buildings by approximately 25-30%. Much of the savings are in regard to the splitting of the sensible and latent loads, but the higher temperature set points of the chilled beams also add to the savings. The direct space cooling of the chilled beams allows the system to operate at a higher design temperatures because of the direct contact to the space. Also, the water being brought to the chilled beams to be used in cooling is usually set around 50^oF. VAV systems are usually designed for the use of 40 to 45^oF water. The higher temperature water is used as an attempt to prevent condensation, but produces additional energy savings that might not be first noticed.

Additionally, the additional rentable space can be seen as an advantage. Chilled beams downsize central mechanical equipment or allow it to be removed. The decrease in mechanical space required as well as the decreases in vertical duct shafts can translate to increase usable space. Also, plenums can become less crowded because of the duct downsizing.

There are a few main drawbacks that are keeping the use of chilled beams in the United States limited. These limitations involve the research and development. For chilled beams to be viewed effective they need to be manufactured within the United States to greatly reduce the cost in comparison to the European produced beams. The production within the United States will spur contractors and engineers to become more familiar with the theory and installation of chilled beams. Other than production, chilled beams need to become more flexible for use in a variety of spaces. The ability to handle higher cooling loads and different flow patterns are two crucial improvements that need to be made to chilled beams in order to fit a larger variety of building types. Also, chilled beams can be seen as having condensation problems.

Redesign Summary

The chilled beams redesign will be completed with the use of Halton, Inc. active chilled beams. Carrier's modeling program HAP was used to model the DOAS/Chilled beam redesign of the Tyler School. Unfortunately, HAP does not offer the ability to model either of these mechanical systems. Therefore, DOAS and chilled beams would need to be created by separating the sensible and latent loads in the Carrier program.

The parallel sensible system is the easiest system to model first. The model would use the same HAP model of the original Tyler School design. The latent occupancy loads were set to zero as well as the outdoor air ventilation requirements. In addition to these changes, the fan energy would need to be altered. The fan energy of the VAV system required an approximate total static pressure drop of between 6 and 8 inch W.G. However, the chilled beams would only require a small pressure drop of approximately 0.5 in. W.G. This decrease is partially offset by an increase in required air changes per hour (ACH) to about 6 ACH. This should provide a relatively accurate understanding of the chilled beams parallel sensible system.

The DOAS model is created from the altered chilled beams model. DOAS models the ventilation loads and the latent occupancy loads. The ventilation occupancy types as stated by ASHRAE Standard 62.1 were used and the latent people load was put back into the program. The sensible loads were all set to zero. This included the lighting, electrical equipment, and sensible people and miscellaneous loads. The roof and wall exposure were also set to zero. This should create a relatively accurate understanding of the ventilation loads as required by each floor.

Supply and Ventilation Air Summary

The amount of ventilation air required by DOAS is greatly reduced in comparison to the original VAVR/CAVR system. Both the redesign and existing system meet ASHRAE 62.1, but often VAV systems are overdesigned because of high minimum settings and the need to make certain that there is adequate ventilation throughout all spaces. The ventilation and supply airs are summarized below.

Ventilation Air Summary

	DOAS Supply Air	Square Feet Served	CFM/FT^2
AHU-1/2	25,336	39,786	0.637
AHU-3/4	31,284	67,333	0.465
RTU-1	19,727	30,757	0.641
RTU-2	8,127	21,749	0.374
RTU-3	8,423	20,410	0.413
Total CFM	92,897		

	Total CFM	Total % Reduction
Original Design	352,000	73
Redesign	92,897	

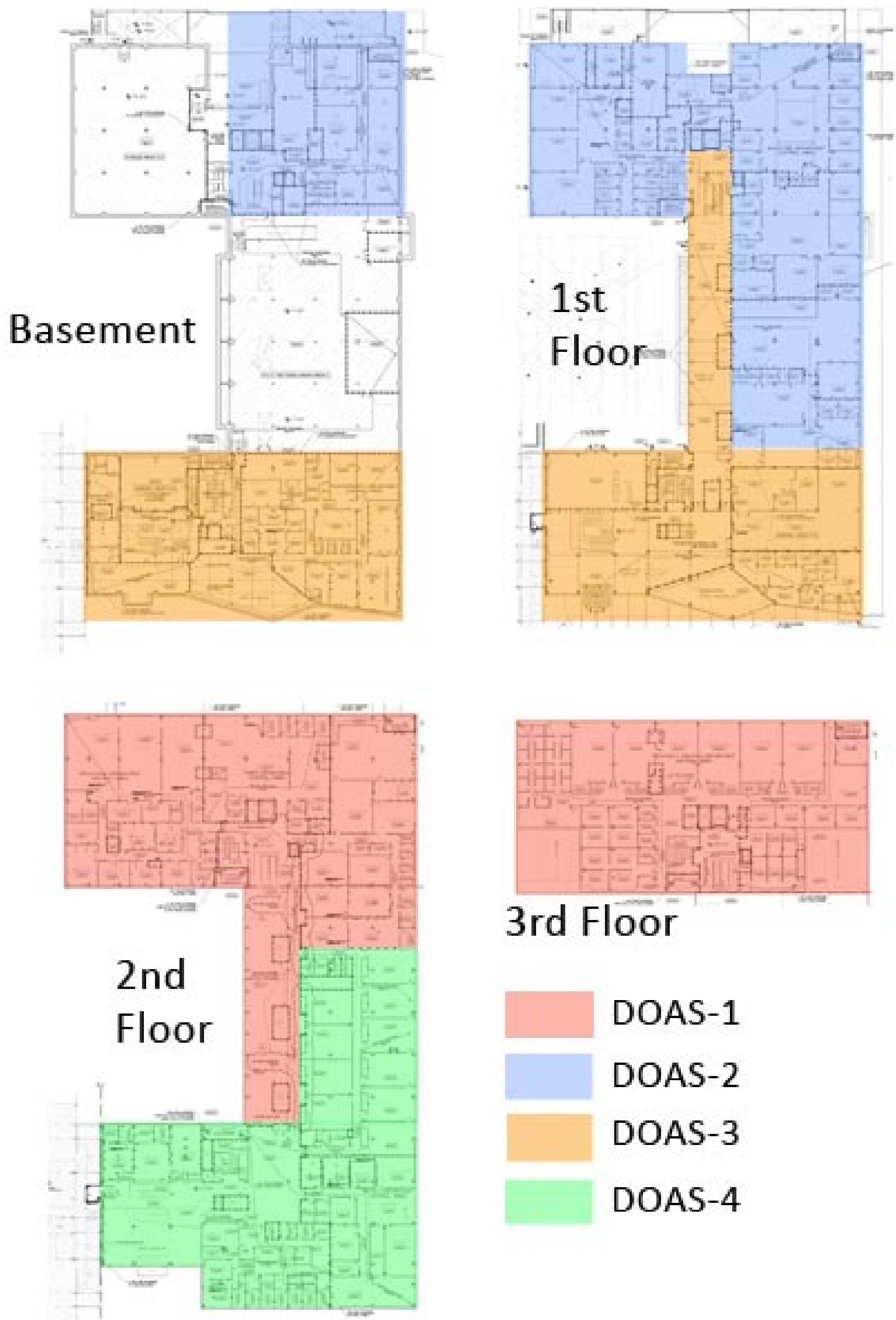
This supply air reduction is important because it means that the seven AHUs and RTUs can be consolidated into four DOAS units as seen below.

DOAS Summary

	Total CFM	Areas Served
DOAS-1	22,213	RTU-2, RTU-3, AHU-3/4
DOAS-2	22,733	AHU-3/4
DOAS-3	25,336	AHU-1/2
DOAS-4	22,615	RTU-1, AHU-3/4

The spaces were able to be consolidated into four zones. The zones still correspond to specific departments, but were split up in a way that sizes all for the DOAS at approximately the same size. The zones are represented below.

DOAS System Layout



Chilled Beams Required

With the use of manufacturer's data, the amount of chilled beams that would be required for the Tyler School of Art sensible load was able to be determined. The table below summarizes the total number of beams that are required by each space. The table shows the number of beams per floor.

Chilled Beams Calculated

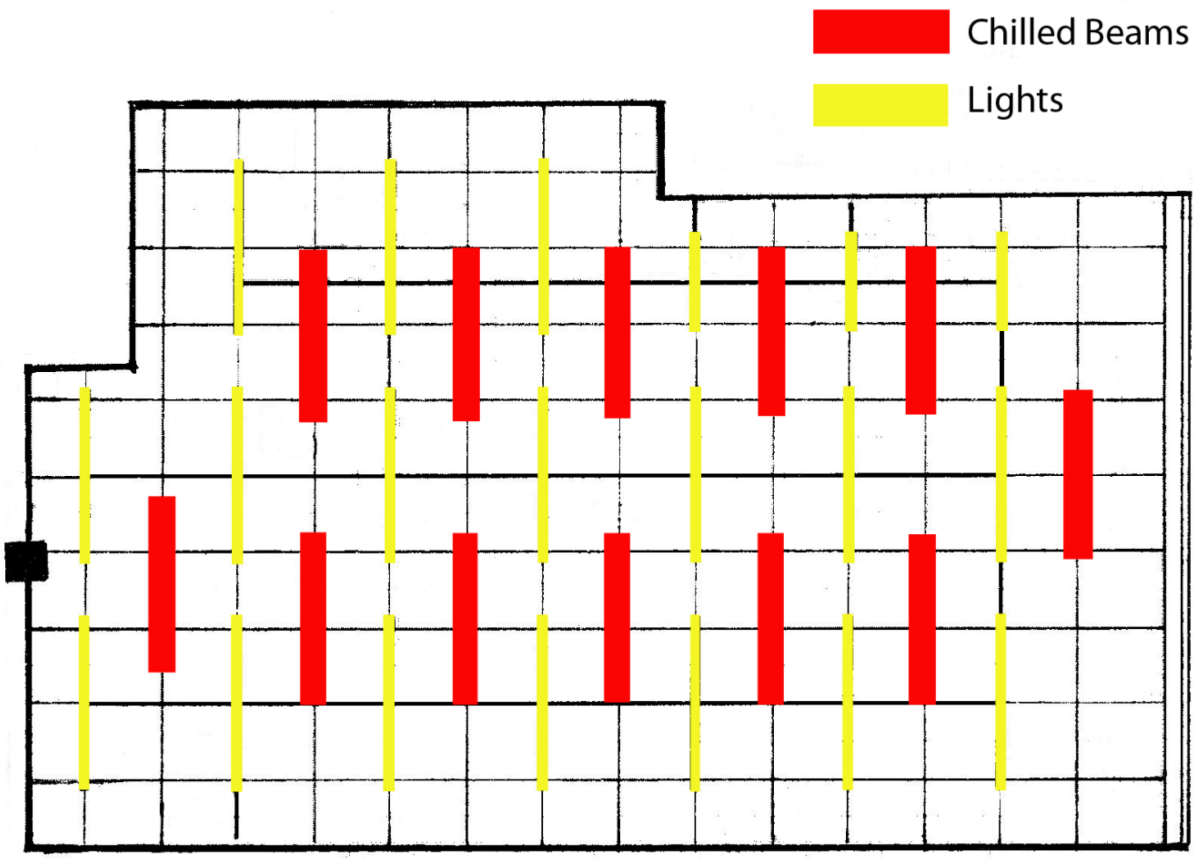
Floor	MBH	Chilled Beams Required
1st	930.2	233
2nd	1344.4	336
3rd	418.8	105
Basement	310.3	78
Total	3003.7	**751**

Chilled Beam Layout of Critical Space

It is important to consider the layout of the chilled beams early in the design considerations. Architects and engineers must communicate design goals early if chilled beams are to be implemented successfully and efficiently. The layout of the chilled beams needs to make sense with the lighting layout. The layout needs to be checked in each room but especially the critical spaces with high sensible loads. One of the downfalls of chilled beams is the inability to handle high loads. One of the critical sensible spaces in the Tyler School of Art was considered below.

The graduate studio room 2101 was considered as a critical space. The sensible load on the space is approximately 36 MBH. Using the information from Halton, Inc. product data, it was determined that almost 12 active chilled beams would be required in this space. The layout of the beams is shown in the graphic below. The chilled beams were calculated to have a length of 10 feet and a width of 16 inches. The studio uses a standard 2 feet by 2 feet grid. The grid below does not show every tile of a reflected ceiling plan, but instead shows the basic 4 feet by 4 feet layout. The layout provides for adequate spacing between the chilled beams and the lighting. The chilled beams selected also have the option for luminaires to be built into the beam itself. This was an option that was not considered further because the additional space was not needed.

Graduate Studio – Room 2101



Economic Analysis

The energy cost comparison was simulated through the Carrier HAP modeling program. The economic analysis for the Tyler School of Art is based upon the electric and natural gas rates as provided by PECO below.

PECO Energy Rates

	Rate	Flat Charge
Natural Gas ($/Therm)	0.2940	$72.01
Electricity ($/kWh)	0.0715	$291.43

Annual Energy Cost

The tables below show the annual energy cost comparison between the two systems.

Existing Mechanical System

		Annual Revised Cost	Total Cost (%)
TYLER SCHOOL ORGINAL DESIGN	Air System Fans	$135,442.00	27.1
	Cooling	$76,924.00	15.4
	Heating	$50,372.00	10.1
	Pumps	$26,110.00	5.2
	Cooling Tower Fans	$32,436.00	6.5
	HVAC Sub-Total	*$321,285.00*	*64.2*
	Lights	$107,486.00	21.5
	Electric Equipment	$71,657.00	14.3
	Non-HVAC Total	*$179,143.00*	*35.8*
	TOTAL	**$500,428.00**	**100**

The design heating load of the existing mechanical system is a little lower than would be normally expected. However, it comes as no surprise that the air system fans are the highest annual cost contribution. The 100% outdoor air demand of AHU-3/4 and RTU-3 as well as the high ventilation rates for the other units explains the high fan energy.

Proposed Mechanical System

		Annual Revised Cost	Total Cost (%)
DOAS	Air System Fans	$42,329.00	24
	Cooling	$33,614.00	19.1
	Heating	$69,548.00	39.5
	Pumps	$13,493.00	7.7
	Cooling Tower Fans	$17,259.00	9.8
	TOTAL	**$176,243.00**	**100**
CHILLED BEAMS	Air System Fans	$19,591.00	12.2
	Cooling	$23,469.00	14.7
	Heating	$18,153.00	11.3
	Pumps	$13,269.00	8.3
	Cooling Tower Fans	$12,408.00	7.7
	HVAC Sub-Total	*$86,889.00*	*54.3*
	Lights	$43,941.00	27.4
	Electric Equipment	$29,294.00	18.3
	Non-HVAC	*$73,235.00*	*45.7*
	TOTAL	**$160.124.00**	**100**

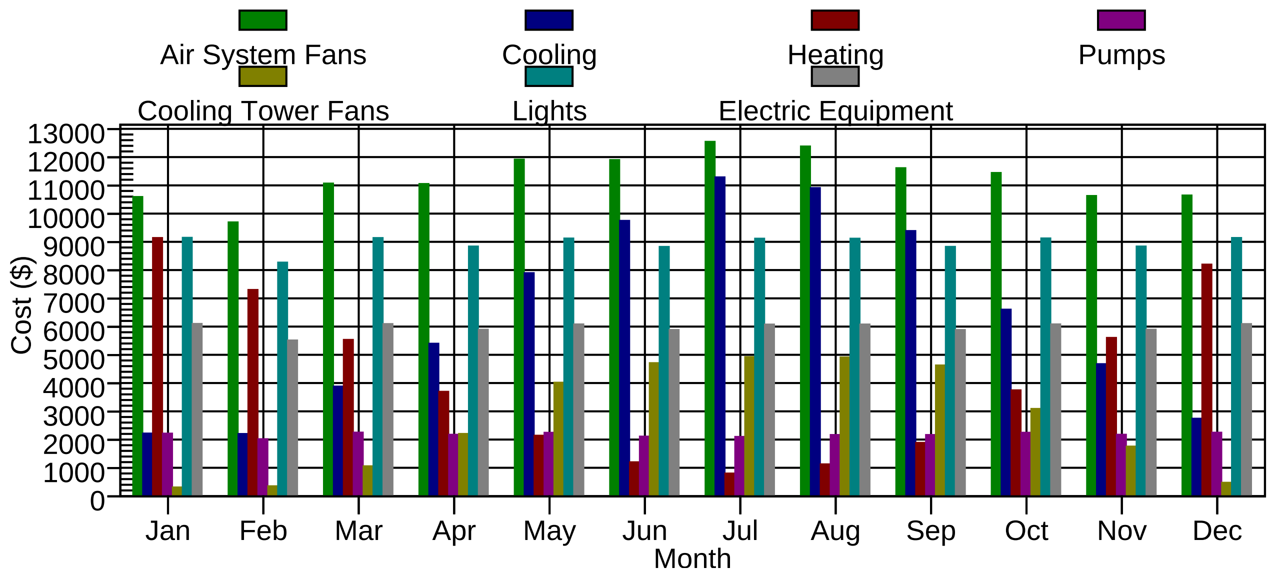
ANNUAL ENERGY COST	
Existing	**$500,428.00**
Redesigned	**$336,367.00**

These tables show that the proposed system featuring DOAS coupled with chilled beams can offer an energy savings of approximately $160,000 per year. This is about a 30% annual energy cost reduction. The switch to the coupled system offers savings with the fan power being exchanged for pumping power. The chilled beams greatly reduce the fan power required by approximately $70,000 per year. Because the chilled beams act directly on the conditioned space, there is no longer a need to use nearly as much fan energy to transfer air from an AHU or RTU to the spaces.

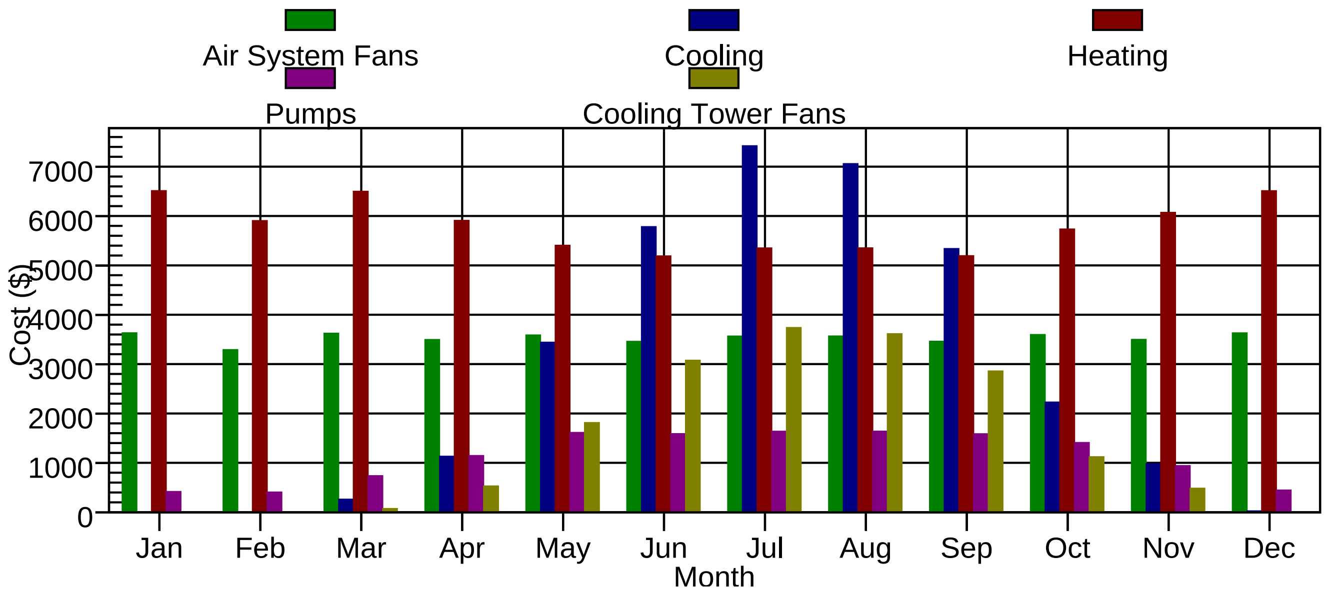
The use of pumping energy instead of fan power is one of the main advantages of the chilled beam parallel system. Pumping energy is much more efficient than fan energy because water has a volumetric heat capacity more than a thousand times greater than that or air. The pump energy will increase because the individual coils of the chilled beams will carry more load than the reheat coil of the VAV system. The cost comparison between the pumps and fans would vary a little from this estimate because there is no exact DOAS modeling program available. The pumping energy would be higher than is expected in this report.

The graphics below show energy costs represented by each mechanical component. The graphics illustrate the cost breakdown on a monthly basis, showing the large fan energy decrease between the present and proposed systems.

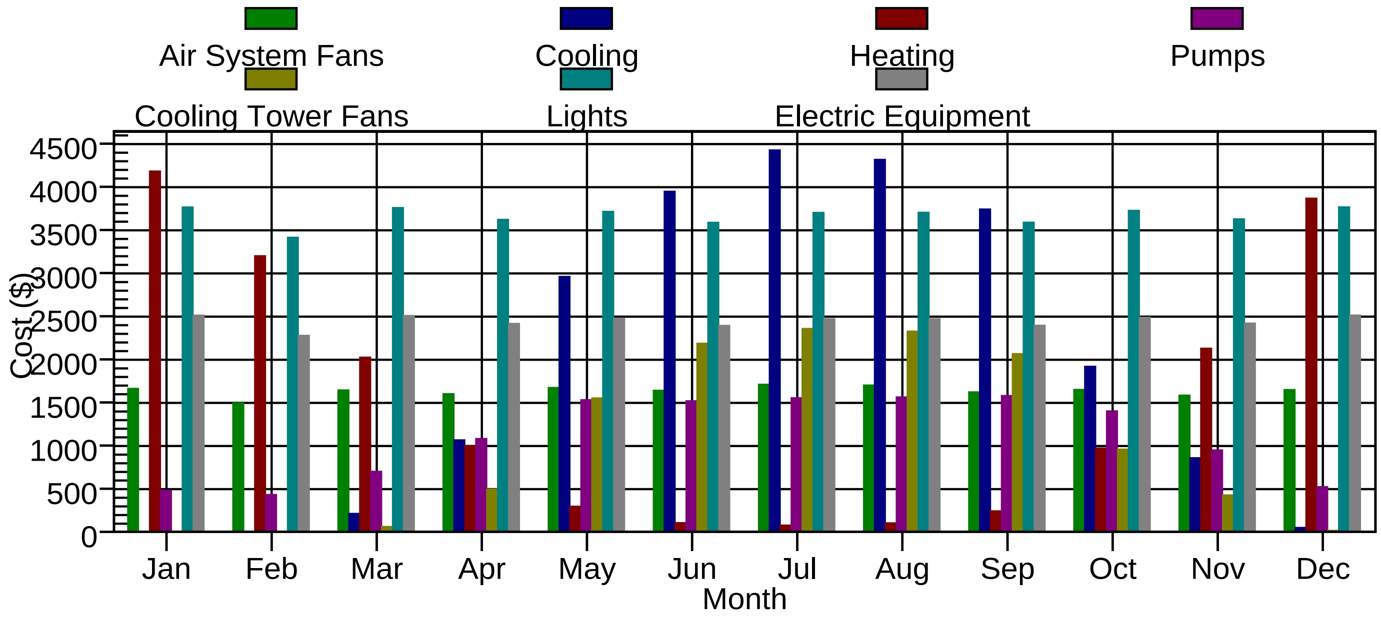
Monthly Component Cost—Existing VAV/CAV System



Monthly Component Cost – DOAS Redesign



Monthly Component Cost – Chilled Beams Redesign



Energy Consumption Comparison

The tables below represent the simulated annual energy consumption for the Tyler School of Art.

Energy Consumption Summary

		Annual Energy Consumption	$/yr
ORIGINAL	*HVAC*		
	Electric (kWh)	3,764,578	$271,240.00
	Natural Gas (Therm)	38,006	$50,044.00
	Non HVAC		
	Electric (kWh)	2,485,585	$179,144.00
	TOTAL ELECTRIC	**6,250,163**	**$500,428.00**

		Annual Energy Consumption	$/yr
DOAS	Electric (kWh)	2,213,175	$161,739.00
	Natural Gas (Therm)	47,034	$14,504.00
CHILLED BEAMS	*HVAC*		
	Electric (kWh)	941,153	$68,854.00
	Natural Gas (Therm)	13,270	$18,035.00
	Non HVAC		
	Electric (kWh)	997,188	$73,235.00
	TOTAL ELECTRIC	**1,938,341**	**$142,089.00**
	TOTAL COST		**$336,367.00**

ANNUAL ENERGY CONSUMPTION		
	Existing System	Redesign
Electric (kWh)	6,250,163	4,151,516
Natural Gas (Therm)	38,006	60,304

The redesigned mechanical system offers a reduction in the electric consumption. The natural gas consumption increases, but in comparison to the considerable reduction in electricity consumption, the natural gas is a secondary factor. The addition of natural gas as opposed to electricity can be beneficial because the rising electricity costs. The reduction also limits the dependency on fluctuating electrical grid pricing by reducing the electrical demand. Natural gas is also an environmental friendly alternative to electric production. The DOAS/chilled beams air pollution reduction can be seen in the emissions summary below.

Emissions

Emissions reduction is an important design consideration. Emissions refer to the air pollution produced as a byproduct of the electricity production. The emissions rates used in the table below were compiled from the Energy Information Administration (EIA) website.

Emissions Comparison

Emissions From Electricity				
	Rates	Existing Emissions	Redesign Emissions	Emissions Reduced
CO_2 (Tons/MWh)	0.782	4887.6 Tons	3246.49 Tons	1641.1 Tons
NOx (kg/MWh)	0.01281	80.06 kg	53.181 kg	26.88 kg
CH_4 (kg/MWh)	0.01404	87.75 kg	58.287 kg	29.46 kg

Percent Emissions Reduction
33.57%

The DOAS/chilled beams redesign produces approximately one-third less emissions than the existing mechanical system. This emissions reduction is crucial for Temple University. University personnel are constantly striving to produce higher efficiency and lower campus emissions.

Breadth –Electrical Redesign

The redesign of the mechanical system has a large impact on the electrical systems in the building. Most of the mechanical equipment is electrical driven. By eliminating the AHUs and RTUs and replacing them with the smaller DOAS units, the electrical system can be downsized. This is an opportunity to decrease the electrical input into the building and offers first cost savings.

All of the feeders were able to be sized down for the redesign. The amps required by the mechanical equipment are dependent on the motor size. The AHUs and RTUs of the existing Tyler School use motors operating between 75 – 100 HP, while the DOAS motors are sized at about 20 HP. The table below summarizes the changes that can be made with the redesigned DOAS mechanical system.

Electrical Equipment Added/Removed

	PROTECTIVE DEVICE			FEEDER					DESCRIPTION
	CB FRAME (AMPS)	NO. POLES	TRIP (AMPS)	NO. SETS	WIRE QTY./SET	CONDUCTOR SIZE (AWG OR KCMIL)	GROUND SIZE PER SET	CONDUIT SIZE PER SET	SERVICE
EQUIPMENT REMOVED	225	3	200	1	3	3/0	6	2	AHU-1
	225	3	200	1	3	3/0	6	2	AHU-2
	250	3	250	1	3	250	4	2 1/2	AHU-3
	250	3	250	1	3	250	4	2 1/2	AHU-4
	225	3	200	1	4	3/0	6	2	RTU-1
	225	3	125	1	4	1	6	1 1/2	RTU-1
	225	3	200	1	3	3/0	6	2	RTU-2
	100	3	100	1	3	1	8	1 1/2	RTU-2
	225	3	125	1	3	1	6	1 1/2	RTU-3
	100	3	100	1	3	1	8	1 1/2	RTU-3
EQUIPMENT ADDED	50	3	45	1	3	10	8	1/2	DOAS-1
	40	3	35	1	3	10	8	1/2	DOAS-2
	50	3	45	1	3	10	8	1/2	DOAS-2
	40	3	35	1	3	10	8	1/2	DOAS-2
	50	3	45	1	3	10	8	1/2	DOAS-3
	40	3	35	1	3	10	8	1/2	DOAS-3
	50	3	45	1	3	10	8	1/2	DOAS-4
	40	3	35	1	3	10	8	1/2	DOAS-4

Voltage Drop

It is important to check to see if the wire size of the redesigned system can handle the voltage across it. Too much voltage can disrupt the starting and operation of the equipment that it serves. The *National Electrical Code* suggests a maximum voltage drop of 3% for branch circuits or feeders. A more conservative maximum voltage drop of 2% was used for the Tyler School. A power factor of 0.9 was assumed for the purpose of finding the voltage drop. The voltage drop check is essential because the feeder lengths of DOAS-4 are both greater than any of the feeders in the existing system. The table below summarizes the feeder lengths and acceptable voltage drop of each DOAS feeder. None of the feeders of the DOAS redesign require a larger wire size.

Voltage Drop							
SERVICE	CONDUCTOR SIZE (AWG OR KCMIL)	FT WIRE	Amps	Voltage Drop Per 1000 Amp-Ft	VD L to L	% VD	Less Than 2%
DOAS-1	10	52	50	1.103	4.96	1.03	Yes
DOAS-1	10	52	40	1.103	3.97	0.83	Yes
DOAS-2	10	56	50	1.103	5.34	1.11	Yes
DOAS-2	10	56	40	1.103	4.27	0.89	Yes
DOAS-3	10	40	50	1.103	3.82	0.80	Yes
DOAS-3	10	40	40	1.103	3.05	0.64	Yes
DOAS-4	10	100	50	1.103	9.54	1.99	Yes
DOAS-4	10	100	40	1.103	7.63	1.59	Yes

Existing Electrical Cost

The existing electrical cost was determined with the use of R.S. Means.

Existing Conductor Costs

CONDUCTOR SIZE (AWG OR KCMIL)	COST PER 100 LINEAR FT.	FT WIRE	TOTAL COST CONDUCTOR	SERVICE
3/0	$370.00	60	$222.00	AHU-1
3/0	$370.00	80	$296.00	AHU-2
250	$565.00	50	$282.50	AHU-3
250	$565.00	45	$254.25	AHU-4
3/0	$370.00	40	$148.00	RTU-1
1	$195.00	40	$78.00	RTU-1
3/0	$370.00	52	$192.40	RTU-2
1	$195.00	52	$101.40	RTU-2
1	$195.00	56	$109.20	RTU-3
1	$195.00	56	$109.20	RTU-3
			$1,792.95	

Existing Ground Wire Costs

GROUND SIZE PER SET	COST PER 100 LINEAR FT.	FT WIRE	TOTAL COST GND WIRE	SERVICE
6	$62.00	60	$37.20	AHU-1
6	$62.00	80	$49.60	AHU-2
4	$97.50	50	$48.75	AHU-3
4	$97.50	45	$43.88	AHU-4
6	$62.00	40	$24.80	RTU-1
6	$62.00	40	$24.80	RTU-1
6	$62.00	52	$32.24	RTU-2
8	$40.50	52	$21.06	RTU-2
6	$62.00	56	$34.72	RTU-3
8	$40.50	56	$22.68	RTU-3
			$339.73	

Existing Conduit Costs

CONDUIT SIZE PER SET	COST PER LINEAR FT.	FT WIRE	TOTAL COST CONDUIT	SERVICE
2	$8.60	60	$516.00	AHU-1
2	$8.60	80	$688.00	AHU-2
2 1/2	$14.00	50	$700.00	AHU-3
2 1/2	$14.00	45	$630.00	AHU-4
2	$8.60	40	$344.00	RTU-1
1 1/2	$6.30	40	$252.00	RTU-1
2	$8.60	52	$447.20	RTU-2
1 1/2	$6.30	52	$327.60	RTU-2
1 1/2	$6.30	56	$352.80	RTU-3
1 1/2	$6.30	56	$352.80	RTU-3
			$4,610.40	

DOAS Redesign Electrical Costs

The DOAS electrical costs were compiled in the same method as the existing Tyler electrical costs.

DOAS Conductor Costs

CONDUCTOR SIZE (AWG OR KCMIL)	COST PER 100 LINEAR FT.	FT WIRE	TOTAL COST CONDUCTOR	SERVICE
10	$46.00	52	$23.92	DOAS-1
10	$46.00	52	$23.92	DOAS-1
10	$46.00	56	$25.76	DOAS-2
10	$46.00	56	$25.76	DOAS-2
10	$46.00	40	$18.40	DOAS-3
10	$46.00	40	$18.40	DOAS-3
10	$46.00	100	$46.00	DOAS-4
10	$46.00	100	$46.00	DOAS-4
			$228.16	

DOAS Ground Wire Costs

GROUND SIZE PER SET	COST PER 100 LINEAR FT.	FT WIRE	TOTAL COST GND WIRE	SERVICE
8	$40.50	52	$21.06	DOAS-1
8	$40.50	52	$21.06	DOAS-1
8	$40.50	56	$22.68	DOAS-2
8	$40.50	56	$22.68	DOAS-2
8	$40.50	40	$16.20	DOAS-3
8	$40.50	40	$16.20	DOAS-3
8	$40.50	100	$40.50	DOAS-4
8	$40.50	100	$40.50	DOAS-4
			$200.88	

DOAS Conduit Costs

CONDUIT SIZE PER SET	COST PER LINEAR FT.	FT WIRE	TOTAL COST CONDUIT	SERVICE
1/2	$2.17	52	$1.13	DOAS-1
1/2	$2.17	52	$1.13	DOAS-1
1/2	$2.17	56	$1.22	DOAS-2
1/2	$2.17	56	$1.22	DOAS-2
1/2	$2.17	40	$0.87	DOAS-3
1/2	$2.17	40	$0.87	DOAS-3
1/2	$2.17	100	$2.17	DOAS-4
1/2	$2.17	100	$2.17	DOAS-4
			$10.76	

Electrical Costs Summary

The table below summarizes the cost comparison between the existing system and the feeders that will change with the DOAS redesign. The electrical cost savings are substantial, but in comparison to the mechanical cost savings they are small. The largest change is seen in the price of the conduit. The large loads of the existing AHU and RTU motors require conduit up to 2 1/2", but the DOAS motors require a much smaller size.

Total Electrical Cost Comparison Summary

EXISTING SYSTEM COST		
CONDUCTOR	*$1,792.95*	
GROUND	*$339.73*	
CONDUIT	*$4,610.40*	
TOTAL COST		**$6,743.08**
DOAS REDESIGN		
CONDUCTOR	*$228.16*	
GROUND	*$200.88*	
CONDUIT	*$10.76*	
TOTAL COST		**$439.80**
Potential Electrical Savings		**$6,303.28**

Breadth - Construction Cost

The addition of DOAS and chilled beams will significantly affect the mechanical cost of the building. A successful redesign must consider the first costs of the revised system as well as the life cycle costs. The life cycle cost analysis will be important for determining the energy effectiveness of the building.

The initial cost estimate below was taken from a combination of R.S. Means, manufacturer's representatives, and contractor estimates. The chilled beams manufacturer Trox suggests 400 Btu/hr and $200/linear foot for the active chilled beams as well as $150/line foot and 180 Btu/hr for passive chilled beams. The active chilled beams estimate was used below. Chilled beams manufacturer, Halton, markets active chilled beams at a similar output, while another manufacturer, Dadanco, offers active beams with an output in the range of 500 Btu/hr per linear foot. The more conservative load was used in this estimate. This cost estimate does not include piping, valves, and other accessories.

Unit Comparison

The much smaller DOAS units provide immediate first cost savings. DOAS handles the ventilation load, which allows the seven AHU and RTUs to be consolidated into 4 smaller DOAS units.

VAV/CAV AHU & RTU		
	CFM	Cost
AHU-1	50,000	$21,100.00
AHU-2	50,000	$21,100.00
AHU-3	62,000	$68,000.00
AHU-4	62,000	$68,000.00
RTU-1	42,000	$43,600.00
RTU-2	51,000	$55,200.00
RTU-3	35,000	$39,300.00
Total		**$316,300.00**

DOAS Units		
	CFM	Cost
DOAS-1	22,213	$30,000.00
DOAS-2	22,733	$30,000.00
DOAS-3	25,336	$30,000.00
DOAS-4	22,615	$30,000.00
Total		**$120,000.00**

Diffuser Cost Summaries

The DOAS/chilled beams redesign offer diffusers cost savings. The localized chilled beams do not require diffusers so there is the opportunity for immediate cost savings. The tables below summarize the breakdown of the diffuser cost.

Diffuser Cost By Floor	
Floor	Cost
Basement	$11,312.50
1st	$17,781.00
2nd	$28,273.00
3rd	$8,489.50
Total	**$65,856.00**

Diffuser Cost Summary		
Size	Total Number	Total Cost
6x6	114	$7,980.00
8x6	30	$2,120.00
8x8	397	$26,640.00
9x9	121	$9,135.50
10x4	20	$1,440.00
10x6	10	$755.00
10x8	8	$775.00
10x10	44	$3,720.00
12x12	20	$1,600.00
15x15	8	$692.00
16x8	6	$800.00
18x18	1	$131.00
22x8	16	$1,280.00
22x14	1	$273.00
10” Diameter	92	$8,463.00
		$65,856.00

VAV Box Cost Summary			
# Units	CFM	Cost	Total Cost
6	200	$670.00	$4,020.00
38	600	$680.00	$25,840.00
35	1,000	$700.00	$24,500.00
30	1,500	$765.00	$22,950.00
25	2,000	$830.00	$20,750.00
3	3,000	$905.00	$2,715.00
		Total Cost	**$100,775.00**

Chilled Beam Summary			
Unit	Max Cooling Required (MBH)	Chilled Beams Required	Cost
AHU-1/2	601	150	$300,000.00
AHU-3/4	933	233	$466,000.00
RTU-1	780	195	$390,000.00
RTU-2	271	68	$136,000.00
RTU-3	419	105	$210,000.00
Total	3,004	751	**$1,502,000.00**

The price of the redesigned system is highly dependent on the price of the chilled beams. The critical laboratory and studio spaces of the Tyler School have high sensible loads, so large number of chilled beams is required. Chilled beams will continue to have very high prices as long as the technology remains mostly European. As more North American companies manufacture chilled beams, the price will decrease and the familiarity of the technology among engineers and contractors will increase, making it a more marketable mechanical option.

Duct Cost Comparison

Existing Duct Cost					
Floor	Duct Surface Area (ft^2)	24 Gauge Duct Thickness (in.)	Duct Volume (ft^3)	Density (lbs/in^3)	Lbs.
Basement	6,746	0.025	14.05	0.285	6,921
1st	10,290	0.025	21.44	0.285	10,558
2nd	11,378	0.025	23.70	0.285	11,674
3rd	6,142	0.025	12.80	0.285	6,302
					35,454

Over 5,000 lbs.	$3.18/lb
Total Cost	**$112,745.17**

DOAS Duct Redesign Cost					
Floor	Duct Surface Area (ft^2)	24 Gauge Duct Thickness (in.)	Duct Volume (ft^3)	Density (lbs/in^3)	Lbs.
Basement	4,048	0.025	8.43	0.285	4,153
1st	6,698	0.025	13.95	0.285	6,872
2nd	6,344	0.025	13.22	0.285	6,509
3rd	3,685	0.025	7.68	0.285	3,781
					21,315

Over 5,000 lbs.	$3.18/lb
Total Cost	**$67,782.18**

Potential Duct Savings	**$44,962.99**

By separating the sensible and latent loads, the duct sizes can be greatly decreased. The DOAS duct would be sized to handle the ventilation loads of the spaces. The active chilled beams still require ductwork but the chilled beams offer local heating and cooling. This translates to much smaller ductwork.

Initial Cost Comparison

The table below summarizes the first costs of the existing Tyler School mechanical system and the DOAS redesign. Mechanical accessories like valves and gauges were not considered in the intial cost comparison because they were assumed to have a roughly equal cost for each system. Chilled beams can offer energy savings with the use of pumping energy as opposed to the less efficient fan energy. The potential additional pump expansion was not considered in the cost comparison.

Initial Cost Summary

	Existing System	DOAS Redesign
CAV AHUs (2)	$136,000.00	
VAV AHUs (2)	$42,100.00	
CAV RTU	$39,300.00	
VAV RTU (2)	$98,800.00	
VAVR Boxes	$100,775.00	
Diffusers	$65,856.00	
Duct	$112,745.17	$67,782.18
DOAS (4)		$120,000.00
Chilled Beams		$1,502,000.00
Electrical Totals	$6,743.08	$439.80
Initial Total Cost	**$602,319.25**	**$1,690,221.98**

First Cost Comparison	**$1,087,903**

The initial cost comparison between the existing system and the redesigned DOAS/chilled beams system show a large price differential of $1,087,903.00. The additional first cost of the redesigned DOAS/chilled beams mechanical can be justified by decreased annual energy consumption, energy cost savings, and mechanical equipment efficiency. The 20 year life cycle cost analysis below will determine if the high initial investment is worthwhile.

Life Cycle Cost Comparison

The energy cost savings of a life cycle cost comparison are expressed below.
Assuming i = 0.06

(P/A, 6%, 20 years) $=[(1+i)^n - 1]/[i(1 + i)^n]$

20 Year Life Cycle Cost

	Existing System	DOAS Redesign
Initial Cost	$602,319.00	$1,690,221.00
Years	Annual Operating Cost	Annual Operating Cost
1	$500,428.00	$336,367.00
2	$500,428.00	$336,367.00
3	$500,428.00	$336,367.00
4	$500,428.00	$336,367.00
5	$500,428.00	$336,367.00
6	$500,428.00	$336,367.00
7	$500,428.00	$336,367.00
8	$500,428.00	$336,367.00
9	$500,428.00	$336,367.00
10	$500,428.00	$336,367.00
11	$500,428.00	$336,367.00
12	$500,428.00	$336,367.00
13	$500,428.00	$336,367.00
14	$500,428.00	$336,367.00
15	$500,428.00	$336,367.00
16	$500,428.00	$336,367.00
17	$500,428.00	$336,367.00
18	$500,428.00	$336,367.00
19	$500,428.00	$336,367.00
20	$500,428.00	$336,367.00
Net Present Worth	**$5,739,869.74**	**3,858,095.85**
Total Cost	**$6,342,188.74**	**$5,548,316.85**

Total Potential 20 Year Savings	**$793,871.89**

The total potential cost savings after 20 years is $793,871,89. This life cycle cost analysis considers initial costs and yearly operational costs. However, the maintenance costs were not considered in this analysis. The DOAS redesign would expect to have a higher maintenance cost because of the complexity and unfamiliarity of the systems, so the life cycle cost would be closer to each other. Also, the central equipment of the VAV/CAV system is what requires most of the maintenance. The localized chilled beams require space specific maintenance. This can complicate the system, especially with the Tyler School carrying such a large sensible chilled beam load.

If the same estimate were used for a 10 year LCC analysis, the savings would not be nearly has great because the initial cost differential is so high. This is not a concern because the building would have a long-term owner. The situation would be different if the building were commercial. The results are summarized below.

10 Year Life Cycle Cost

Annual Cost	$500,428.00	$336,367.00
NPW	$3,683,193.64	$2,475,690.40
Initial Cost	$602,319.25	$1,690,221.98
LCC	$4,285,512.89	$4,165912.38

Total Potential 10 Year Savings	**$119,600.51**

The break even time period for the system to be entirely paid back is 8.71 years. This payback period helps to justify the redesign of the Tyler School mechanical system. In some DOAS cases the payback period can be even far less than 8.71 years. By downsizing and eliminating mechanical equipment, the savings can be seen almost immediately or in the first cost. The Tyler School has a slightly longer payback because the amount of chilled beams required to handle the sensible space loads.

Mechanical Depth Conclusions

The DOAS/chilled beams mechanical redesign offers obvious energy benefits. By greatly reducing the electrical energy required, the system reduces annual energy costs and emissions. In some cases, the payback for DOAS with chilled beams can be even less and sometimes immediate. The Tyler School system payback of 8.7 years is short enough to warrant the redesign in this case.

There are a few obstacles in the way of the Tyler School mechanical redesign. In theory, the system works well, but many of the barriers are in the industry itself. DOAS is not widely used in the industry. Energy modeling programs like Carrier's HAP, Trane Trace, or E-Quest do not have DOAS simulation capabilities. This is obvious because Carrier or Trane do not manufacturer DOAS units. However, manufacturers need to offer simulation programs that can be used to model the energy savings as well as the humidity and indoor air quality control potential of the system.

In the same way, chilled beams suffer from the same lack of exposure. As a long time accepted European technology, chilled beams have had difficulty making the jump to the United States market. The lack of the North American manufacturers leads the need to rely on European technology. This leads to unfamiliarity with the system by engineers and contractors. This unfamiliarity can cause chilled beams to be viewed as having too high of a first cost to be effective. Another hurdle involving the use of chilled beams can be the design coordination required. As the industry continues to become more integrated among disciplines this problem will disappear. It is important for there to be coordination early in the design process between the architects and engineers for the layout of a localized parallel system like chilled beams to be effective.

As the use of DOAS with a parallel sensible system becomes more prevalent and accepted in all building construction markets, the system benefits will become clearer and the design will become simplified. The education on this technology will also grow.

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Appendix

Design Criteria

Space	Design Temperature		Relative	Total	Outdoor	Exhaust	Room
	Cooling	Heating	Humidity	ACH	ACH	Room Air	Pressure
Administration& Offices	72	72	50-60	4	1	No	Even
Assembly Areas	72	72	50-60	6	2	No	----
Auditorium	72	72	50-60	6	2	No	Even
Cafeteria	75	75	50-60	6	2	No	Positive
Classroom	75	75	50-60	6	3	Yes	Even
Computer Lab	72	70	50-60	6	1	No	Even
Conference Rm	72	72	50-60	4	1	No	Even
Control Rm, Computer Rm	72	70	40-50	6	2	No	Even
Corridor	78	70	----	2	0.1/SF	No	Even
Electrical Rm	80	70	----	----	10	Yes	Negative
Gallery-Student	72	70	50-60	8	2 to 4	No	Even
General Storage	80	70	50-60	4	2 (min)	Yes	Negative
IDF Rm	72	72	50-60	4	1	No	Even
Kiln Rms	80	70	----	6	2 to 6	Yes	Negative
Labs	75	72	40-50	10	10	Yes	Negative
Loading Dock	----	65	----	----	----	Yes	Negative
Lobby & Atrium	75	75	50-60	4	1	No	Positive
Locker Rms	78	75	70	10	0	Yes	Even (TA) [1]
Mechanical Rm	----	80	----	----	2(min)	Yes	Negative
Music Rm	75	75	50-60	----	----	No	Even
Painting Studios Storage[2]	72	72	55-65	6	6	No	Negative
Shops	80	72	50-60	----	----	Yes	Negative
Studio	75	75	50-60	----	----	Yes	Negative
Studios, Storage	78	70	50-60	6	2	Yes	----
Telephone Rm (Main)	72	70	40-50	4	0	No	Even
Telephone Rm (Satellite)	75	70	40-50	2	0	No	Even
Toilet Rm & Janitor Closet	78	70	----	10	10	Yes	Negative (TA) [1]
Vending Area	78	70	----	4	0	Yes	Negative
Vestibule	80	65	----	4	0	No	Positive
Waiting Rm	75	75	50-60	4	1	No	Even

[1]TA = Transfer Air
[2]Room requiring humidity control

Appendix

Occupancy Requirements

Space	ASHRAE Max Occupancy P/1000 SF	ASHRAE OA CFM/P[1] CFM/SF[2] CFM/WC[3]	Avg People Loading Quantity[4]	Avg People Sensible Heat Gain (Btuh)
Administration & Offices	7	20	1/150 SF	245
Assembly Areas	120	15	----	----
Auditorium	150	15	1/7 SF	----
Cafeteria	100	20	1/10 SF	----
Classroom	50	15	1/20 SF	245
Computer Lab	60	20	1/16 SF	245
Conference Rm	50	20	1/20 SF	245
Control Rm, Computer Rm	40	15	1/50 SF	250
Corridor	----	0.1/SF	0	250
Electrical Rm	20	0	0	275
General Storage	10	15	0	245
Labs	30	20	1/33 SF	----
Lobby & Atrium	30	15	1/33 SF	250
Locker Rm	20	0.5/SF	0	245
Music Rm	50	15	----	----
Painting Studio Storage	50	15	1/20 SF	----
Shops	30	20	1/33 SF	----
Studios	50	15	1/20 SF	----
Telephone Rm (Main)	20	0	0	275
Telephone Rm (Satellite)	20	0	0	275
Toilet Rm & Janitors Closet	----	75/WC&Urinal	0	245
Vending Area	----	----	0	275
Vestibule	----	----	0	250
Waiting Rm	60	25	----	250

[1]Value based on people loading unless indicated otherwise based on International Mechanical Code 2003
[2]Where the value is based on area, minimum total OA is the product of value and area
[3]Where the value is based on water closets (WC), minimum OA is the product of the # of water closets and urinals in the space
[4]Where the value is based on area, minimum occupancy loading is the quotient of area and value