Dormitory optimized energy performance using spatial archetypes

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ABSTRACT

Achieving good building energy performance has been a major challenge in architecture but has intensified over the past twenty years. Today, the constant increasing cost of energy and the environmental impact of production and energy use make reduced energy use a significant objective in the design and operation of buildings. This paper addresses the general problem of minimizing building energy consumption and the associated operational costs of HVAC systems in an existing building.

1. INTRODUCTION

Over the past years, building performance simulation has been used for energy analysis. Availability of such tools enables realistic use of mathematical optimization, the approach followed in this paper. Optimization can be used to improve building performance.

The aim of this paper is to test a methodology that enables the categorization of built spaces with similar thermal behavior, namely spatial archetypes. These spatial archetypes are created based on realistic architectural design problems where various built forms can be represented by one unique, which takes into account basic design standards. More specifically, these standards include furniture, building, ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers) and geometric standards. With the use of optimization, competing objectives were examined and in specific the building loads and thermal comfort.

The methodology created was tested with a demonstration study. However, the spatial archetype developed was for a very simple building design scenario. The study would benefit by applying the methodology of spatial archetypes, in a real case of an existing complex building. Therefore, the Bursley Hall Dormitory of the University of Michigan, in Ann Arbor was used. In the case study conducted, the effort was mainly focused on identifying built forms that appear repeatedly inside the building and propose spatial archetypes that would encompass thermal behavior.

2. DESIGN PROBLEM

The existing dormitory is composed of four buildings that have different orientations: the south-east wing, the south-west wing, the north-west wing and the north-east wing (see Figs. 1 and 2).

Each wing-building floor is at a different ground level following the ground landscape. The ground floor of each wing is an entire floor height higher than the previous one, starting first from the south-east wing, going to the south-west wing, then onto north-west wing and finally the north-east wing (Fig. 3). Each wing has four floors. If all four wings are taken into account, there are totally seven floors starting from the ground level.

An analysis was conducted on the existing situation of the building in relation to room sizes, frequency of appearance, wall dimensions and orientation. Table 1, shows the different rooms that were found, with their dimensions and characteristics for the first level of the south-east wing building. However same study was done for each building floor and wing sepa-

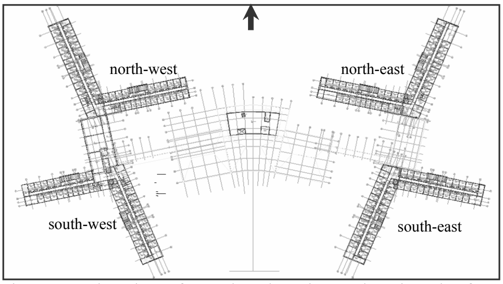

Figure 1: The plan of Bursley dormitory showing the four different wings.


Figure 2: A picture of Bursley Hall Dormitory showing the south-west wing with its landscape.

rately. The dimensions of the room, the fenestration area, the wall thickness, and the orientation have an implicit impact on the thermal behavior of the building. Therefore, these elements define multiple types of built forms (shown on first column of the table). Same materials were considered for all wing building. A four-inch common brick with insulation was used for the exterior wall and a four-inch common brick with plaster for the interior walls. In the second column of Table 1, the occurrence of rooms that have same properties is shown. The next three columns illustrate the x, y, z room dimensions representing the width, length and height of the room. The next two columns show the width and height of the fenestration area. The word *all* means that the window width stretches throughout the room width.

The wall thickness column shows the thickness of the right wall, the thickness of the wall where the door is, the wall where the fenestration area lies, and the left wall respectively. Properties of the location (for example if it is next to stairs) and the general size of the room (for example a small or middle size room) are next. Finally, the table shows the orientation and how many degrees off east, north, west or south the room looks at.

All building floors were examined for their room types. It was observed that a middle size room (mr) with the same dimensions and wall thickness occurred 634 times throughout the building. Therefore it would be useful to find the optimum properties for such a room for all orientation and floor of the building so that minimum energy consumption is achieved while maintaining thermal comfort (Fig. 4).

An analysis of the room for each wing building level and each orientation was done

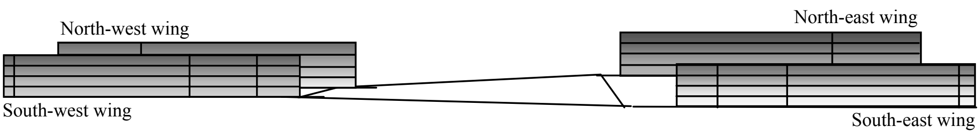

Figure 3: Elevation Graph of Bursley Hall.

Table 1: Bursley Hall Rooms, as they exist on the first floor of the south-east wing building.

Bursley	Type	#	x	y	z	xwin	ywin	wall thickness				looking in-out	degrees off
								r	d	f	l		
first floor													
s-e wing													
	1	1	138.5	200.5	96	all	56.63	13	6	3.5	5.5	next to stairs	22 off west
	2	9	138.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle	
	3	4	102.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle small	
	4	1	260	200.5	96	all	56.63	5.5	6	3.5	16	corner big room	
	5	1	138.5	200.5	96	all	56.63	17.8	6	3.5	5.5	next to stairs	22 off east
	6	8	138.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle	
	7	1	138.5	200.5	96	all	56.63	18.8	6	3.5	5.5	next to stairs	12 off north
	8	6	138.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle	
	9	1	282	200.5	96	all	56.63	5.5	6	3.5	39.8	big room all interior	
	10	1	260	200.5	96	all	56.63	5.5	6	3.5	16	corner big room	12 off south
	11	8	138.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle	
	12	4	102.5	200.5	96	all	56.63	5.5	6	3.5	5.5	middle small	

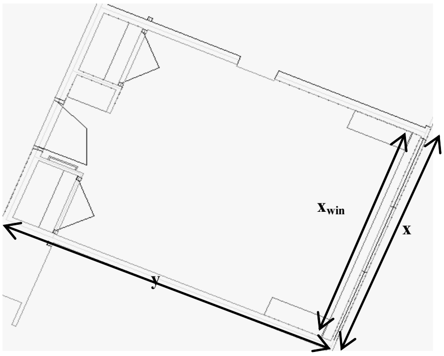

Figure 4: The middle size room.

lating Heating and Cooling Loads and Predicted Mean Value (PMV) average, an indicator of thermal comfort. For these calculations Energy Plus (Crawley et al., 2002) was used. A simulation of the existing situation (base case) for all four wings for their thermal performance (Loads and PMV average) was done. Table 2 is a sample of this analysis and shows the existing situation (base case) for only the first 2 floors of south-west and south-east wings.

In order to decide which rooms would be considered for the proposed methodology, some assumptions were necessary. By analyzing the results, it was noticed that the orientation the south-east wing building and the north-east wing building was the same (Fig. 1). Similarly, the orientation of the south-west wing building and the north-west wing building was also the same. Thus, only the south-west and south-east wings were examined.

In Table 2, the first line, the orientation of the room from the true north is shown the temperature average is calculated as an indication of the temperature inside the room. Heating and Cooling loads and the total loads are also shown. Finally, the PMV average is shown. Each column represents the four different orientations of each wing. By examining the results, it was obvious that the orientation and room level was a significant factor in terms of room thermal behavior. Further analysis was conducted to verify such remarks, where optimization was taken into account.

Therefore, first this type of the middle size room was optimized with respect to Heating and Cooling Loads, and then for the PMV average. For the optimization, the Sequential Quadratic Programming (SQP) algorithm was used (SQP is a gradient-based optimization algorithm) through Matlab (Mathworks, 2002), and the objective function values were computed from Energy Plus. The constraints considered were related to bounding the variables (minimum and maximum values), which were the dimensions of the room and the fenestration area.

A comparison of the two optimization problems for each orientation, for each wing (south-east and south-west) and for each floor was

Table 2: Base case for first and second building floors.

2	South-East-Wing North-Middle 1st Floor	South-East-Wing East-Middle 1st Floor	South-East-Wing South-Middle 1st-Floor	South-East-Wing West-Middle 1st Floor	South-West-Wing North-Middle Ground	South-West-Wing East-Middle Ground	South-West-Wing South-Middle Ground	South-West-Wing West-Middle Ground
angle north	102	202	282	22	78	158	258	338
temp avg	21.1327859754	22.5193594505	23.2474399910	21.9373372843	20.5759162793	20.9312963517	21.6397494761	21.4251096800
Heating	2.409683E+09	1.775113E+09	1.110608E+09	2.165155E+09	1.442623E+09	1.364682E+09	8.946496E+08	1.096219E+09
Cooling	1.031068E+10	1.249503E+10	1.222325E+10	1.252408E+10	7.739911E+09	8.241046E+09	8.451584E+09	9.190000E+09
Total	1.272037E+10	1.427014E+10	1.333386E+10	1.468924E+10	9.182534E+09	9.605729E+09	9.346233E+09	1.028622E+10
PMV-Avg	0.4235127470	0.6418726200	0.7907705709	0.5356311767	0.3475601031	0.4029683630	0.5274042191	0.4736386340

1	South-East-Wing North-Middle Ground	South-East-Wing East-Middle Ground	South-East-Wing South-Middle Ground	South-East-Wing West-Middle Ground
angle north	102	202	282	22
temp avg	20.5483918820	21.3478419559	21.6782077469	21.0708311791
Heating	1.436847E+09	1.155309E+09	8.562962E+08	1.312477E+09
Cooling	7.594153E+09	8.565125E+09	8.556713E+09	8.881802E+09
Total	9.031000E+09	9.720434E+09	9.413009E+09	1.019428E+10
PMV-Avg	0.3452197353	0.4742718704	0.5341625212	0.4167647489

Table 3: Comparison of the two optimizations of the base case

2	South-East-Wing North-Middle 1st Floor	South-East-Wing East-Middle 1st Floor	South-East-Wing South-Middle 1st-Floor	South-East-Wing West-Middle 1st Floor	South-West-Wing North-Middle Ground	South-West-Wing East-Middle Ground	South-West-Wing South-Middle Ground	South-West-Wing West-Middle Ground
Temp dif H&C	-1.4252481107	-0.7031857913	0.1001978953	-1.3052311165	-0.1718005885	0.0609518905	0.6171552820	0.3959263121
Heat dif	-7.990284E+09	-9.418454E+09	-9.806953E+09	-9.089614E+09	-6.067138E+09	-6.316785E+09	-6.755857E+09	-6.875452E+09
Cool dif	9.688489E+09	1.199032E+10	1.169377E+10	1.203359E+10	6.957382E+09	7.459493E+09	7.719722E+09	8.440687E+09
Total dif	1.698205E+09	2.571865E+09	1.886819E+09	2.943979E+09	8.902440E+08	1.142708E+09	9.638647E+08	1.565235E+09
PMV dif	-0.3560476038	-0.2427386402	-0.0724809149	-0.3556302506	-0.0815150194	-0.0431588551	[illegible]	0.0083063223
Total %	13.3503%	18.0227%	14.1506%	20.0417%	9.6950%	11.8961%	10.3129%	15.2168%
PMV %	-84.0701%	-37.8173%	-9.1659%	-66.3946%	-23.4535%	-10.7102%	11.5419%	1.7537%
Temp dif PMV	0.5263185308	1.1881962998	1.5994433892	0.9007571120	0.3109241612	0.4602562243	[illegible]	0.6498547155
Heat dif	-7.020415E+09	-8.816133E+09	-9.367608E+09	-8.393213E+09	-5.835316E+09	-6.229548E+09	-6.856506E+09	-6.997797E+09
Cool dif	7.272391E+09	9.942379E+09	1.015644E+10	9.652680E+09	5.902897E+09	6.487597E+09	7.112720E+09	7.684671E+09
Total dif	2.519758E+08	1.126245E+09	7.888364E+08	1.259467E+09	6.758140E+07	2.580490E+08	2.562141E+08	6.868748E+08
PMV dif	0.1072629718	0.2076570462	0.2932376432	0.1561068963	0.0781639237	0.1005415732	0.1536231023	0.1224910354
Total %	1.9809%	7.8923%	5.9160%	8.5741%	0.7360%	2.6864%	2.7414%	6.6776%
PMV %	25.3270%	32.3518%	37.0825%	29.1445%	22.4893%	24.9502%	29.1282%	25.8617%

PMV H&C

1	South-East-Wing North-Middle Ground	South-East-Wing East-Middle Ground	South-East-Wing South-Middle Ground	South-East-Wing West-Middle Ground
Temp dif °C	-0.1741590183	0.3570348620	0.6323104670	0.1312612507
Heat dif	-6.004778E+09	-6.618680E+09	-6.835131E+09	-6.596302E+09
Cool dif	6.803314E+09	7.807996E+09	7.844802E+09	8.120480E+09
Total dif	7.985362E+08	1.189315E+09	1.009671E+09	1.524179E+09
PMV dif	-0.0799494924	0.0098924506	[illegible]	-0.0391593264
Total %	8.8422%	[illegible]	10.7263%	14.9513%
PMV %	-23.1590%	2.0858%	11.8405%	-9.3960%
Temp dif	0.2981256151	0.6444816991	[illegible]	0.5307558125
Heat dif	-5.760975E+09	-6.656435E+09	-6.935657E+09	-6.586516E+09
Cool dif	5.764235E+09	7.003164E+09	7.262190E+09	7.152724E+09
Total dif	3.259542E+06	3.467287E+08	3.265326E+08	5.662079E+08
PMV dif	0.0773612666	0.1307359119	0.1550320514	0.1071089234
Total %	0.0361%	3.5670%	3.4690%	5.5542%
PMV %	22.4093%	27.5656%	29.0234%	25.7001%

PMV H&C

done for the first two building floors.

The differences in values between the base case and the optimized case for Heating and Cooling (H&C) and for PMV average were calculated and a sample is shown on Table 3. Positive values indicate improvement from the base case and negative values indicate deterioration. Percentages were also calculated to help demonstrate the overall idea. The percentages are the differences of the optimized and the base case values over the base case values. Such comparison indicated that the observations done in the base case were valid even after the optimization. It was noticed for example, the behavior of the south facing room of the ground floor of the south-east wing was similar to the south facing room of the ground floor of the south-west wing (circles in Table 3). Therefore, the built forms that were considered were representative of the floor level rather than the orientation or the wing building.

Based on the quantitative observations, two built forms were considered, one for the south-east wing (sew) and one for the south-west wing (sww) building to apply the methodology. However, three different problem formulations were created and each considered these two built forms, one for each floor separately (ground, middle, top). The middle floor represents both the second and third floor, since their thermal behavior was approximately the same. The same objectives and constraints were considered for both rooms, and their differences appeared mainly in parameters that were embedded in the calculations of the objective functions. These were calculated using the Energy Plus; Throughout this case study, the purpose was to keep the overall structure of the building. Thus, the dimensions of the building and the orientation of the wings and the rooms were taken into

Table 4: Design variables for Product.

MIDDLE ROOM	
x_{mr}	X dimension of the room floor
y_{mr}	Y dimension of the room floor
z_{mr}	Z dimension of the room (height)
x_{win}	Width of fenestration area
y_{win}	Height of fenestration area

account, as they exist currently.

3. MATHEMATICAL FORMULATION

3.1 Design Variables

The variables used as mentioned before were the room size (x_{mr}, y_{mr}, z_{mr}) and the window size (x_{win} and y_{win}). They are shown on Table 4.

3.2 Objective Function

In this case-study as aforementioned, both Heating and Cooling Loads as well as PMV average were used for the design objective functions. The average for all four orientations of the rooms in each wing building is assumed for both the Loads and the PMV average.

$$f_1 = L_h + L_c,$$
$$f_2 = PMV_{avg} \quad (1)$$

where L_h, L_c and PMV_{avg} functions were computed using the simulation software Energy Plus and were dependent on all design variables.

3.3 Constraints

The constraints were divided into building standards, requirements for furniture functionality, ASHRAE standards and geometrical requirements.

3.3.1 Building Standards

1. Total Area: The total area of the floor of the room should be at least 70 square feet, as posed by the National Building Code Compliance Manual (Parish, 1998). In addition, each of the width and length of the room plan dimensions should not be less than 2.134 meters.
2. Ceiling Height: The ceiling height of the room was required to be less than 5 meters and more than 2.134 meters high.
3. Window area: The minimum window area for natural ventilation and natural lighting according to the national building code compliance was 0.36 square meters. Additionally operable exterior openings should occupy at least 4% of the total floor area for natural ventilation. Similarly, the openings should occupy at least 8% of the total floor area for obtaining natural lighting.

3.3.2 Geometric standards

Some geometric constraints were related to window size not exceeding the wall size. A 2.5 centimeters margin around the window ensured the proper construction of such window area.

3.3.3 ASHRAE Standards

Thermal Transmittance Value (U_o value): Any residential building that is heated and mechanically cooled should have a combined thermal transmittance value for the gross area of exterior walls not exceeding the value of 0.26 in Detroit, where the heating degree-days are 6569 (ASHRAE, 2001).

3.3.4 Furniture Requirements

Total floor area: For a floor area to accommodate the furniture for a dorm, three different values were given (De Chiara, 2001). Minimum required area was 6.5 square meters, best suggested was 11 square meters and generous 18 square meters. Only the upper and lower limits were used, letting the optimization problem determine the best values for the present problem:

The constraints used are shown below and with some simplification, the problem formulation is shown below:

min: $f_1 = L_h + L_c,$

$f_2 = PMV_{avg}$

subject to:

$g_1 : 6.5 - x_{mr} y_{mr} \leq 0$

$g_2 : 2.134 - x_{mr} \leq 0$

$g_3 : 2.134 - y_{mr} \leq 0$

$g_4 : z_{mr} - 5 \leq 0$

$g_5 : 2.134 - z_{mr} \leq 0$

$g_6 : 0.36 - x_{win} y_{win} \leq 0$

$g_7 : 0.04 x_{mr} y_{mr} - x_{win} y_{win} \leq 0$

Table 5: U values for the wall and window materials

U_{Aw}	Transmittance value of the wall (0.22 btu/ft^{2}F*h or 0.04 W/m^{2}K)
U_{Af}	Transmittance value of the windows (0.45 btu/ft^{2}F*h or 0.08 W/m^{2}K)

$$g_8 : 0.08x_{mr}y_{mr} - x_{win}y_{win} \leq 0 \qquad (2)$$

$$g_9 : x_{win} - x_{mr} + 0.27 \leq 0$$

$$g_{10} : y_{win} - z_{mr} + 0.27 \leq 0$$

$$g_{11} : 0.04[x_{mr}z_{mr} - x_{win}y_{win}] + 0.08x_{win}y_{win} 0.06x_{mr}z_{mr} \leq 0$$

$$g_{12} : 11.36 - x_{mr}y_{mr} \leq 0$$

$$g_{13} : x_{mr}y_{mr} - 18 \leq 0$$

$$g_{14} : 2y_{mr} - 10.2 \leq 0$$

$$g_{15} : 4z_{mr} - 12 \leq 0$$

The values used for the materials of the room described earlier are shown on Table 5.

4. SIMULATION

Similar to the demonstration study, a computer simulation was used to compute the objective functions. Activity inside both rooms, lighting and mechanical system installations were taken into account. In addition, information about the different orientations of each floor in each wing was also taken into account.

5. RESULTS

Four different design scenarios of commonality were examined in each of the problem formulations (top floor, middle floors and top floor). Similar to the demonstration study, first a total platform (mr_total) was considered. Additionally, sharing all variables but the ceiling height (mr_height), sharing all except the room dimensions (width and length, mr_walls) and sharing all except the window dimensions (width and height, mr_windows) were the rest of the platforms that were examined.

The four platforms were generated for each of the floors separately; ground floor (Fig. 5), middle floors (Fig. 6) and top floor (Fig. 7). The x axis shows the total loads in Billions of Joules (1e10J) and the y axis shows the PMV average values. The circles indicate the design selection for each problem formulation.

Overall, it was noticed that as the floor level increased, both Heating and Cooling Loads and

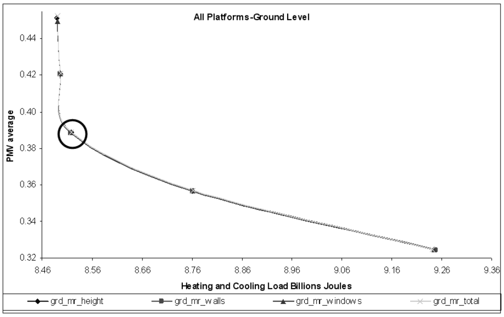

Figure 6: All Platforms for the Ground Level room.

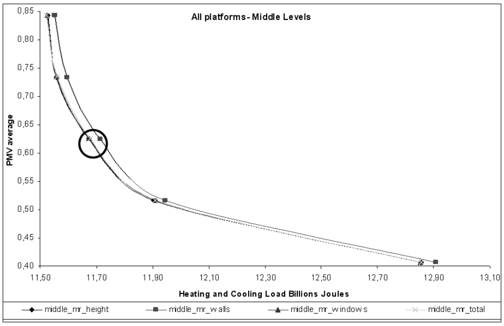

Figure 7: All Platforms for the Middle Level room.

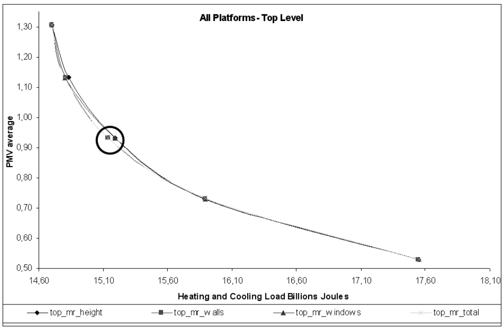

Figure 8: All Platforms for the Top Level room.

PMV average value also increased. This was expected, considering that a top floor is more exposed to wind, cold and sun than the ground level, therefore it needs more energy for heating and cooling and it is harder to reach the comfort level. It was also observed that all platforms in each floor had almost the same Pareto curve. A careful analysis was conducted to ensure that such results were not due to some mathematical or problem formulation errors. It was first checked whether the problem was constraint driven where it would only allow for a very small area of feasibility, therefore generate similar pareto curves. A new problem formulation was conducted for the middle level room according to Equation 6.6 and three new platforms were generated, (mr_height, mr_windows, mr_walls), using only half of the constraints. More specifically, all constraints were eliminated except the ones that were bounding the variables ($g_2, g_3, g_4, g_5, g_9, g_{10}$).

The results indicated that even though there were considerably less constraints, the Pareto Curves of the three platforms generated were almost the same. It was additionally shown that without some of the constraints the problem had better solutions. This was because some of the constraints that kept the geometry analogy were not present. Therefore, even though all platforms seemed to have better values on the objective values, the variables were taking optimal values that were violating the standards (geometry, ASHRAE, building and furniture standards). Based on these observations, it was certain that the constraints were not creating any errors in the results of Figures 5, 6 and 7.

In addition to the constraint driven problem, an additional issue checked was all obtained points on the pareto curves were different designs for each platform. This meant that the variables on each of these points had different values. As checked points with similar objective values had different design solutions. This also eliminated the possibility of the optimization algorithm error, falling into local minima each time, therefore generating same results.

These observations were enough to show that there was no error in the Pareto curves, and so the selection of the solution point should be made that would represent the archetypes for each floor separately.

6. CONCLUSIONS

All points in each of these curves were optimum for the problem posed (Equation 2). Therefore, any of these would be a good solution for a minimum Heating and Cooling Loads and for a thermally comfortable area (PMV average close to zero). Selecting the design solution was based both on the graphs of Figures 6, 7 and 8.

First, the main criterion was to select the platform that shared the most variables. Therefore, the total platform would be the best choice for each level. Again maximum floor size, maximum fenestration area, and a constant height for the room inside each floor were the geometric criteria that were also considered.

Table 6: Base Case and Optimized Solutions.

	x_{mr}	y_{mr}	z_{mr}	x_{win}	y_{win}
Base Case	3.51	5.09	2.44	3.31	1.43
Ground Level	3.93	4.58	2.13	1.05	1.37
Middle Level	3.30	4.91	2.13	1.86	0.7
Top Level	3.65	3.95	3.12	1.24	0.93

Based on these criteria, the solutions of Figures 5, 6 and 7 were selected (circle in each figure with platforms for all levels).

From the solutions of Table 6 it is obvious that small changes in the architectural design have a significant effect on the overall thermal behavior of the building. All variables, except the window dimensions did not appear to be much different from the base case. The most important observation was that the window size would have to be reduced in order to have a better thermally-behaved space. Further analysis on the results, showed that these changes had a considerable impact on the operational costs of the room and therefore of the building.

Based on DTE Energy in Detroit, Michigan, it was calculated that a middle size room saved between 112 and 271 US dollars per year. Using the three archetypes throughout the Bursley Hall would provide overall savings per year on an average of $106650. This amount is significantly large considering such small changes that were required for the design of the room.

This case study showed that the methodology analyzed is applicable and can be used in real complex buildings. Three archetypes were created that were optimized for their thermal performance, each representative of a building level taking into account building, furniture, ASHRAE and geometric standards. It was shown that small changes in the architectural design can yield to significant improvement of the thermal behavior and the operational costs of the building.

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