Preliminary Concept Design (PCD) Tools for Laboratory Buildings, Automated Design Optimization and Assessment Embedded in Building Information Modeling (BIM) Tools

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Abstract. The design of laboratories entails the implementation of a variety of design constraints such as building codes, and design guidelines; the application of these requires from designers the derivation of data not explicitly available at early stages of design development. Many of these constraints deal with providing secure conditions for the activities inside laboratories and their repercussions on both occupants and population in general; some of these mandate a strict control over the building’s Heating Ventilating and Air Conditioning (HVAC) system. Due to the importance of these constraints, laboratory designers are commonly expected to assess not only spatial relationships in their designs, but also variables such as HVAC efficiency, air pressure hierarchies, operational costs. During preliminary concept design (PCD) of laboratories, the assessment of technical constraints is usually done by domain experts using manually extracted data; the evaluation is performed mostly through manual calculations or building simulations, the turn around of these might take hours or days depending on the methods used by the engineer, reducing then the possibility for design alternatives evaluations. The results of the evaluations give clues about sizing of the HVAC equipment, and might generate the need for design reformulations, causing higher development costs, frictions within the design team, and time delays [32].

Efforts in the development of automated design evaluation such as; wheel chair accessibility [6], security and circulation [27], and construction codes [1] have demonstrated the capabilities of rule or parameter based building assessment; several computer applications supporting HVAC engineers in system design for late concept design or design development have been produced, but little has been done to support HVAC engineering during PCD [32]. Developments in computer
Aided design (CAD) such as Building Information Modeling (BIM) have open doors to formal explorations in generative design using rule-based or parametric modeling [17] [5]. BIM represents buildings as a collection of objects with their own geometry, attributes, and relations. BIM has facilitated the development of automated rule-based building checking [27].

Here we analyze the possibilities of BIM to implement design assessment, particularly in the domain of laboratory design. In this schema, domain specific knowledge is embedded in to BIM software as to make explicit design metrics that can help architects and engineers (AE’s) to assess the performance of design alternatives. We argue that the implementation of generative design assessments during PCD helps AE’s to identify design issues early in the process, reducing the number of reconfigurations in later stages of design, and generally improving design performance. The research described here is the result of the work developed by; AEC integration Laboratory at the College of Architecture Georgia Institute of Technology, General Services Administration (GSA), the Federal Drug Administration (FDA) and the collaboration of Kling & Stubbins Architects, Washington DC.

1. Aim of the study

There are many theories on how designers perform design tasks [33, 13, 14], but it seems to be of common agreement that designers elaborate different representations of design problems in order to solve them, these can have many forms such as line based diagrams, space program charts, block diagrams, etc. Designers also develop strategies, such as checklist or flowcharts to deal with large numbers of variables including design constraints and technical requirements [13, 14]. Among these the line based and block stacking diagrams seem to be well suited to PCD because of their simplicity and flexibility.

"Automating this process has the potential to alleviate both the delays and the inconsistencies associated with manual checking by giving the designer and the permit-issuing body a consistent framework in which to apply and check codes"[6].

During laboratory PCD, most of the information available to AE’s in traditional representations is geometrical in nature, most of data derivation for design assessment centers on area calculations, in this schema there is no explicit link between design and the guidelines or the engineering data affecting them. For instance; traditional HVAC calculation during PCD demand for the HVAC engineer to manually extract information such as space geometry from 2D data, calculate heat gains, aggregate the results to building level information, compute the required cooling loads, either manually or using building simulation software, and provide preliminary specifications for the HVAC equipment.
This study looks for ways in which BIM can assist AE’s when performing laboratory PCD evaluations related to specific design guidelines [3, 4, 28, 31] and to demonstrate how basic assessment capabilities can be implemented by end users without the need of extensive programming expertise. This study in no way tries to eliminate domain experts such as HVAC engineers, on the contrary, tries to provide consistent and easily sharable data among AE’s, as means of improving collaboration among design team members that can easily generate fictions and reformulations [32].

2. Problem definition

During laboratory PCD, information tends to be limited to spatial layouts, these are usually done by establishing relationships between three different spatial components: laboratory area, Mechanical/Electrical/Plumbing (MEP) space or service area, offices, and if needed laboratory support area in one of the latter two. Many models of spatial layouts have been tried through the history of laboratory design, recently and because of increasing demands over building systems and growing concerns regarding operational costs; the space to space relations between laboratories-MEP-office areas have received lots of attention from AE’s [21-22].

2.1. Preliminary Concept Design (PCD) of Laboratories

The type and extent of design assessments and the possibilities of data derivation during PCD are constrained by the semantic complexity and level of completeness of the data contained in the BIM. The FDA-PCD tool operates within the semantic bounds of early design development as identified in the GSA Facilities Standard (P100), specifically in the phase identified as Preliminary Concept Design [9]; here the minimum contents of the BIM during PCD are defined in terms of semantic contents, as follows:

Preliminary concept: placement and massing of the building are defined, program spaces are identified only at a departmental level, circulation either vehicular and human areas are identified, no internal partition walls or wall openings, basic definition of building boundary surfaces (Figure 1).

Later stages of design, such as Late Concept, Design Development and Construction Documents, follow. During these the information contained in the design will continuously gain both in definition and content. What in preliminary concept design might be a simplified bubble diagram will evolve in to a Late Concept design proposal (Figure 2).
Fig. 1. Preliminary concept design diagram NIH design policies and guidelines, Office of Research Facilities/ National Institutes of Health, Department of Health and Human Services USA, 2003.
There are many classifications for laboratories, a high level classification is that of dry or wet laboratory, where wet laboratories involves working with solutions and require piped services, work benches, and sinks; dry laboratories involve the use of electronic equipment with very specific electrical services but fewer requirements for piped services. A different way would be to classify laboratory spaces regarding the type of activity developed within them [2], such as chemical, biological, biochemical, physical, and psychological. Laboratories are also classified by the biological safety level required form the space. The Biological Safety Level (BSL) [23], in this classification there are four levels BSL1, BSL2, BSL3, and BSL4, for facilities dealing with animal species the classification is ABSL1, ABSL2, ABSL3, and ABSL4. With BSL4 being the highest level of containment.

2.3. PCD spatial programming for laboratory buildings

The main spatial referent for laboratory spatial programming is the laboratory module. These should be understood as a referential modular space free of any obstructions. Full detailed technical specification of each laboratory module is achieved in late stages of design and in cooperation with the laboratory director,
but is during PCD when the sizing of the modules and the relationships between these and the different program components is established. When dealing with animal research facilities the main spatial referent is the animal holding room, the dimension of it is usually constrained by the cage or rack system selected.

The sizing of the laboratory module allows AE’s to define a PCD layout of the building’s structural grid, and to have an approximation to the occupancy load of the facility. The definition of the laboratory module facilitates also the standardization of MEP services per module. The recommended minimal usable width for each laboratory modules is 11 ft considering an aisle width of 5 ft. and laboratory benches of 3 ft. on each side, the ideal usable depth of the module is 33 ft. [3, 4]. Depending on design conditions the laboratory module can include two other program components: scientist office and lab support space. The spatial relations among these will affect not only human circulation conditions but it will impact in the dimensioning of the mechanical systems of the building. For instance, the inclusion of the scientist office within the of the laboratory module, will negatively affect the load on the HVAC system by increasing the area of conditioned space, but the detachment of these might negatively increase the length of pedestrian circulation required to connect the two spaces. Another concept of spatial programming of laboratory facilities is that laboratory neighborhood or laboratory wing, these work as grouping of laboratory spaces around a number of researchers, it operates under the premise of grouping scientists and their operations to avoid the duplication of expensive support area. Numbers of configurations for laboratory spaces, neighborhoods or wings have been identified [2, 4, 5] these configurations are usually analyzed by the relationship between the laboratory spaces and service corridors or service shafts [2, 4, 5].

2.4. Indoor conditions in laboratory buildings

The importance of the indoor conditions in laboratory buildings goes far beyond providing adequate working environments; they play a fundamental role in providing the right conditions for experimental procedures and in protecting users from contaminants. In general laboratory spaces air supply must be 100% outside air no recirculation is permitted for the ventilation of these. To prevent cross contamination a system of air pressures should be designed in which laboratory spaces must have negative pressure regarding their surroundings. In general laboratory space recommended temperature is 73 F summer and 70 F winter, both with a variation of ±1.8 F, the relative humidity should be 50% ±5% for the summer and 45% ±10 % during the winter [4]. These conditions are to be maintained 24 hours a day, 7 days a week [3].
2.5. Incorporating HVAC design into PCD of laboratories

There is a clear concern on increasing the efficiency of laboratory buildings [19]. The cost of a HVAC systems in laboratories can account for 20% to 40% of the building initial cost [26], over 50% of the energy consumption of a typical laboratory facility is due to ventilation. Even though there are many computational tools that help AE’s in the design of HVAC systems [25], they are not well tailored for PCD and their use still requires either extensive domain expertise or vast amounts of input data that might not be available during PCD [24]. In this context even domain specific tools such as Autodesk Revit MEP, do not contain in their default interface, design tools to support architectural PCD, and to calculate heating load require form domain specific inputs.

The FDA - PCD tool allows designers to analyze different design alternatives and their performance regarding cooling loads and ventilation requirements, helping them to optimize the spatial layout and the HVAC zoning definition. This type of assessments during laboratory PCD can help AE’s to make informed design decisions, which will have a direct impact in both the construction and operational costs of the facility. The tool helps AE’s to explore alternative solutions to the ventilation system such as the use of face velocity drop in air handlers.

3. Implementation approach

With the idea of having timely assessment feedback without the need of data exports or application programming interfaces we decided to embed the FDA-PCD tool into a BIM application and use its default interface. This has been achieved through the use of a project template embedded with parametric constraints; these constraints represent the building type heuristics required for the assessment (Figure 3). The selected approach eliminates the need for users to learn a new tool. For the implementation of the FDA-PCD tool we looked among contemporary BIM for the following capabilities;

- Parametric control of geometric entities
- Instantiable parametric objects
- Availability of sharable class level parameters
- Ease of parameter control in the user interface

One critical factor when deciding for our hosting application was the ease of user’s access to both parametric control and assessment feedback; we decided to embed the FDA-PCD tool in Autodesk Revit. Besides being wide spread within the industry [20], Revit in its default structure provides; family objects these are instantiable parametric objects which can contain both instance and class level
parameters; these parameters can be controlled either by mathematical formulas or conditional statements. Revit’s structure also allows for the definition of shared parameters; these establish the interaction between the family objects and the project environment, allowing for instance for the computation of values embedded in family objects within the project environment. Both parametric control of variables and assessment feedback can be associated to Revit’s schedules (Figure 5), these are filtered views of the BIM data, they can be easily customized to display both geometry and attribute based information, this can be achieved with different levels of aggregation. In the FDA-PCD tool we use; zone, level, and building aggregations

![Diagram](image)

*Fig. 3. FDA-PCD building block component, laboratory block parameters.*

The implementation of the FDA-PCD tool required from two different approaches for embedding building type heuristics into the BIM software. Firstly, the geometric constraints and conditionals statements controlling the behavior of the family objects were embedded in family object internal parameters. Secondly, the computations for the different types of feedback were implemented in to Revit’s schedule views, these schedule views were configured in to the FDA-PCD template file. The interrelation between family objects and schedule views was established through shared parameters. These allow for the extraction of parameters form the family objects, and act as user interface by enabling the end user to customize the attributes and the behavior of the different family objects available.
4. Automated layout generation for laboratory design

A successful design assistant should provide designers with valuable information while recognizing the nature of design processes. Since our efforts are centered in the PCD phase, providing a tool capable of giving designers the flexibility of traditional design tools has been considered important by the developers.

"Another aspect of drawings to be considered is the level of abstraction of the information to be represented. During the design process, the design is refined from an abstract concept to a final, detailed, drafted design"[7].

For the FDA–PCD tool we have developed two modeling approaches supporting the evolutionary nature of design; the line based layout tool and the parametric building block, these are intended to support high levels of abstraction characteristic of PCD, and at the same time allow designers to incrementally improve the semantic complexity of the BIM model, while keeping the required FDA-PCD assessment capabilities.

4.1. Building block automated layout tool

One of the features of BIM software is the availability of parametric objects; these are geometric entities with specific behavioral rules, for instance doors objects in most BIM environments contain rules that allow them to be inserted only in wall objects. For the FDA-PDC automated layout tool we have identified those BIM objects which rules allow them to be instantiated in plan projections, in the case of the block stacking models, and to line objects for the line based component. We have extended the governing rules of these objects as to include the PCD laboratory domain specific heuristics [3, 4, 28].

The automated block based layout tool has been developed under the assumption that; designers might choose to start the PCD by producing massing diagrams of the building, these type of diagrams allow them to analyze the formal implications involved in the stacking of 3 dimensional (3D) building blocks (Figure 4), with each of the blocks representing the different programmatic components The FDA–PCD tool provides designers with parametric building blocks covering the basic departmental units identified in section 4, the defined categories are; office wings, laboratory wings and service core. These in their default setting contain the different semantics associated to program components commonly found in laboratories space types. These blocks can be instantiated by the modeler in the project environment and customized depending on design needs through the parameters available in the schedule view.
The parametric building blocks in the FDA-PCD tool provide information; not only about the geometry of the building block, but also regarding the efficiency of the spatial arrangement. For instance in the parametric lab wing the default conditions have been set up to 50ft, deep with lab modules 33ft depth and 11ft wide, after designers modified the values for the width of the laboratory wing or the laboratory module, the lay out tool automatically adjusts the number of lab modules to the given conditions.

The FDA-PCD tool contains three classes of programmatic building blocks; the laboratory building block, the office building block, and the service core block. High levels of customization can be achieved by adjusting the parameters of these block components (Figure 9), two types of geometric customization can be obtained, firstly; the block based component geometry can be manipulated to adjust to different types of arrangements, typologies such as double loaded corridor building wings can be easily produced through the controls contained in the respective parametric schedule; secondly; user’s can customize the block by changing the component controlling parameters, this can be done in their

<table>
<thead>
<tr>
<th>Level</th>
<th>Lab Block Depth</th>
<th>Lab Block Width</th>
<th>Lab Block Corridor Width</th>
<th>Number of Modules</th>
<th>Lab Block Corridor Loaded Corridor</th>
<th>Lab Block Corridor Option</th>
<th>Reverse Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>33' - 0&quot;</td>
<td>400' - 0&quot;</td>
<td>12' - 0&quot;</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Level 2</td>
<td>33' - 0&quot;</td>
<td>350' - 0&quot;</td>
<td>15' - 0&quot;</td>
<td>13</td>
<td>1</td>
<td>1</td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Fig. 4. FDA-PCD Block based layout tool, massing study.

Fig. 5. FDA-PCD parametric laboratory block schedule, control parameters.
respective parametric schedules views (Figure 5). For instance, the parameters associated to the block based components are:

- **Block depth**: length value which defines the depth of the building block.
- **Block length**: length value which defines the length of the building block.
- **Corridor**: Boolean value indicates the existence of a corridor along the building block.
- **Corridor Width**: length value which defines the width of the corridor if this element exist.
- **Module Width**: length value indicating the required length of each module.
- **Double loaded corridor**: Boolean value, defines the existence of a double loaded corridor in the building block.
- **Reverse direction**: Boolean value; reverses the position of the corridor regarding the building block.
- **Number of modules**: computed number of modules which would fit in the building block.

For the service core building block and understanding that this component is commonly instantiated in other spaces, the parameters have been laid out in such way that if the service core block is instantiated inside a space object, its area will be automatically reduced form the area calculations of the hosting space. Users can modify not only the geometric properties of the building block but also manipulate the attributes of elevator units embedded in it (Figure 6). The control parameters available for the service core building block are:

- **Service Core Depth**: Length value, defines the depth of the laboratory wing.
- **Service Core Width value**: informs the system the designed width for each office module.
- **Elevator Depth**: Length value of each elevator in the service core.
- **Elevator Width**: Length value of each elevator in the service core.
- **Elevator Units**: Integer value of elevator fitting in the service core.

![Service Core Parameters Schedule](image)

*Fig. 6. Service core parameters schedule.*
4.2. Line based automated layout tool

Space arrangements for laboratories are also organized as neighborhoods or arrays of spaces, this is known as laboratory and office wings (Figure 7). The line based layout tool in the FDA–PCD tool supports automated design assessment of this type of spatial arrangements by embedding the semantics commonly associated to laboratories into BIM objects whose instantiation is defined by a length datum. In order to deal with a wide variety of building shapes, we have developed two line based components; one deals with linear arrangements of building wings, the other with curved ones.

There are two basic protocols for using the FDA-PCD line based component; in the first AE’s draw curves by using the selected FDA-PCD line component, the component and all its geometric and semantic contents are deployed automatically along the length datum, in the second AE’s develop a curve based diagram, and after completion of it, they can assign to each of the curves the selected FDA-PCD line based building component, the instantiation process will recognize the length of the selected curve and apply on to it the semantics defined for each of the FDA-PCD line based building components. In its default set up the line based \ layout component deploys basic programmatic semantics for the selected component such as laboratory wing type (Figure 8), or office wing. All the building program semantics and parametric behavior for each of the components have been embedded in the Family types, in similar way as the parameters of the building block component (Figure 4).

Two types of geometric customization can be achieved in the line based layout components. First the line based component can read the length of its length datum therefore any change in the length datum automatically updates the computations associated to it. Second the user can customize the object by changing the values controlling the component (Figures 9, 10), these can be
modified by accessing the parameters in each respective schedule view, such as the "parametric lab wing schedule" (Figures 9, 10). The control parameters available for the FDA_PCD line based building components are:

- **Corridor**: Boolean value indicates the existence of a corridor along the building wing.
- **Corridor Width**: length value which defines the width of the corridor if it exists.
- **Module Width**: length value indicating the required length of each space module
- **Adjusted module width**: the adjusted value for the module length regarding the length datum.
- **Wing depth**: length value which defines the depth of the Building wing
- **Double loaded corridor**: Boolean value defines the existence of spaces organized around a double loaded corridor in the building wing.
- **Reverse direction**: Boolean value reverses the location of the corridor regarding the building wing.
- **Number of modules**: computed number of space modules which would fit in the building wing for the established parameters.

Multiple configurations can be assessed by modifying the parameters in the line based component; these parameters are contained in the schedule view (Figures 9, 10). Schedules also contain the assessment feedback, such as the number of modules and the adjusted dimensions of each of the program units in the building wing. For instance; when analyzing the implications of the design in Figure 7, the use of Line based components makes possible the automatic assessment of laboratory modules and office units for the selected arrangement.

The design information made explicit by the system can be seen when comparing three PCD diagrams (Figure 8) such as; line based diagram, bubble diagram and the one constructed using the FDA-PCD line based component. Even though these are produced in similar manner the level of feedback provided by them is different, in the case of the first diagram the only explicit information. For the bubble diagram the space classes and a visual approximation ratio between them is available. Most of the information contained in these two types of diagrams is still implicit in the AE’s head, any metric regarding the layout needs to be computed either manually or using some rule of thumb. In the case of the FDA-PCD diagram a combination of laboratory and office wings can be used to build the same arrangement, but in this case the information for occupancy loads is readily available in the associated schedules (Figures 9, 10). At the same time the system applies recommended minimum dimensions [3, 4] to different space classes.
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**Fig. 8.** Design diagrams produced by the system arranging office and laboratory spaces similarly to those in Fig. 14. To the left line based diagram, center bubble diagram, to the right FDA-PCD line based components.

<table>
<thead>
<tr>
<th>PARAMETRIC OFFICE WING</th>
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<tbody>
<tr>
<td>Off Module W</td>
</tr>
<tr>
<td>11' - 0&quot;</td>
</tr>
<tr>
<td>11' - 0&quot;</td>
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<td>11' - 0&quot;</td>
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<td>11' - 0&quot;</td>
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<tr>
<td>11' - 0&quot;</td>
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<tr>
<td>Grand total</td>
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**Fig. 9.** FDA-PCD Office line based component, interface for the PCD diagram in Fig. 8.

<table>
<thead>
<tr>
<th>PARAMETRIC LAB WING</th>
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</thead>
<tbody>
<tr>
<td>Lab Module W</td>
</tr>
<tr>
<td>20' - 0&quot;</td>
</tr>
<tr>
<td>20' - 0&quot;</td>
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<tr>
<td>20' - 0&quot;</td>
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<td>Grand total</td>
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**Fig. 10.** FDA-PCD Laboratory line based component, interface for the diagram in Fig. 8.

The nature of the geometric behavior differentiating both straight lines and curves has prompted the development of independent line based component to deal with curved building wings. The FDA-PCD curve is an arc based component which provides automated feedback for the same parameters implemented for the straight line component.
The implementation of the parametric behavior of the FDA-PCD curve component family type is hidden from the end user within the family types of the component, in it simple Euclidian geometry calculations have been implemented to control the behavior of the component and to produce feedback regarding the curved wing. An example of the family type interface can be seen in the building block component (Figure 4).

Geometric customization of the curve based automated layout component can be performed by changing the behavioral parameters in the respective schedule (Figure 12), also by manipulations on both the length datum and the "Curve Handle" which is included in the schedule as "Arc handle distance".

5. Generative design assessment

The concept Generative design assessment is based in the implementation of smart building representations, by embedding knowledge in the generative end of design; rules are applied, evaluated or informed while the design is being produced, reducing the need of post design assessment or data migration to external applications or the development additional data structures additional to those in the BIM application since these might will not be updated during application run time every time a change is introduced to the design.

The process depends on the types of computations needed for the assessment and the type of data in the available in the BIM model. The computations...
embedded in the FDA-PCD tool use parameters already available in the BIM model, more accurately the parameters explicit in space objects, such as space name, and gross area. Derivation of data is also implemented for those assessments requiring mathematical manipulations in order to produce feedback for AE’s.

The implementation of generative based design assessment requires from the BIM application the capability of linking parameters and calculations to specific BIM objects. The implementation of the FDA-PCD tool has explicitly connected both parametric calculations and space objects through the definition of a domain specific space name taxonomy; Laboratory space, Office space, Circulation Space. These cover the requirements for PCD departmental units for laboratory design and directly constraint execution of the FDA-PCD tool utilities.

5.1. Using Autodesk Revit’s schedules as assessment interfaces

Among the multiple representations of data available in Autodesk Revit, this software can display schedules as hierarchically organized views of building data. These are used in the FDA-PCD tool as end user interfaces, the assessment schedules contain fields for all the required inputs, at the same time these display the design feedback computed by the tool. We have developed 8 different types of assessment schedules views.

Laboratory schedule (Figure 13); upon users input of the occupancy ratios for each of the spaces labeled "Lab Space", the schedule provides feedback on the expected occupancy for each laboratory space instance, this helps AE’s to constantly verify occupancy requirements without the need to perform manual computations. Here the AE’s can also analyze the percentage of space which could be dedicated for laboratory support area by providing the system a percentage of the laboratory space which to be used for this purpose.

![Laboratory schedule](image)

Program Efficiency schedule (Figure 14); provides AE’s with automated calculation of the area efficiency for all the spaces defined in the PCD laboratory BIM model. The efficiency schedule displays the ratio of each space class, regarding the gross area of each building level, helping the AE’s to analyze requirements compliance such as efficiency of circulation areas in relation to building gross area.
OFFICES schedule (Figure 15); based on the occupancy ratios, the Office schedule provide feedback regarding the expected occupancy loads and gross area for each of the office space instances. The information is displayed both in a level by level or entire building aggregations, the office schedule also provides PDC calculations of internal heat loads for its use in the base line load calculation (section 7), the heat gains are based in number of occupants, task light per occupant, and room lighting.

Walls schedule (Figure 16); skin area information allows for the evaluation of the possible cost efficiency between different design alternatives, at the same time it provides information for late concept design energy calculations which require detailed data regarding the composition of the building skin. The wall schedule displays geometric information both aggregated and at individual levels.
**Base line loads schedule** (Figure 17); provides AE’s with data that supports the PCD pre-sizing of the HVAC components, the information provided by this schedule view, can be directly associated to a equipment manufacturer specifications in order to estimate the sizing of both the water side and the air side components. The schedule contains the following parameters;

- **Load**: refers to the internal heat load in the space, measured in Watts per Square Foot.
- **H in**: enthalpy of the air entering the HVAC system, it is measured in Btu per Pound of air.
- **H out**: enthalpy of the air leaving the HVAC system; it is measured in Btu per Pound of air.
- **EAT**: refers to the temperature in Fahrenheit of the air entering the system.
- **LAT**: refers to the temperature in Fahrenheit of the air leaving the system.
- **VFD speed**: refers to the cubic feet per minute defined for the calculation of velocity face drop.

Extensive explanation for both internal loads and enthalpy values can be found in section 7

![Fig. 17. FDA-PCD Base line loads schedule.](image)

### 6. FDA-PCD automated cooling load calculations

The calculation of accurate cooling loads to support the functioning of laboratory buildings HVAC systems requires for the evaluation and computation of multiple domain specific parameters, many of which are not commonly known by architectural designers [29] The processes in most cases requires the use of building simulation software, most of these are labor intensive and require the HVAC engineer’s expertise. In most of the cases building simulations require a vast number of inputs and the elaboration of building models separate from the BIM model used during architectural design [24, 30, 34]. Despite the fact that commercially available CAD tools such as Autodesk Vasari provide PCD energy analysis capabilities. The energy analysis still depends on web based servers, and is unable to pair the speed of the design decisions typical of PCD which can be measured in a couple minutes [8].

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1. The data presented in the previous schedules represents the feedback for a building model one story height with 5066 sq ft.
Traditional calculation methods during PCD require for the HVAC engineer to manually extract information such as space geometry from design data [34], calculate the heat gains for each space, aggregate the results to building level information, and provide a specification for the equipment. Among the HVAC information derived from PCD laboratory data is that of spaces cooling loads. These allows for the better understanding the buildings cooling requirements, the pre-sizing of air side and water side systems. The automation of cooling load calculations not only integrates HVAC engineering data to PCD but it also eliminates the need for performing design data derivations by the HVAC engineer, and allows AE’s to easily analyze the impact of design alternatives in the performance of the HVAC system.

6.1. Computations of cooling loads

The base line load schedule in the FDA-PCD tool; is the basic interface to assess the cooling requirements of the facility, the information here is presented in two levels of aggregation; level by level, and entire building. To complete the calculations of cooling loads AE’s are required to manually input the following parameters:

- Load = defined by program (W/sq ft²)
- h in = enthalpy² in (Btu/Lb)
- h out = enthalpy out (Btu/Lb)
- EAT = entering air temp (Fahrenheit)
- LAT = leaving air temp (Fahrenheit)
- VFD speed = air velocity for velocity face drop calculations (CFM)

The following are the computations currently implemented in the FDA-PDC tool for the purpose of preliminary calculations of cooling loads:

\[
\text{Delta } h = h \text{ in} - h \text{ out} \quad \text{difference between the enthalpy in and enthalpy out of the HVAC system} \\
\text{Delta } T \text{ airside} = \text{LAT} - \text{EAT} \quad \text{difference between the leaving temp and the entering temp} \\
\text{Total Air flow} = \text{Load} \times 3.41 \times \text{Area} / (1.09 \times \text{Delta } T \text{ airside}) \quad \text{the result of it this is CFM} \\
\text{Sensible heat} = \text{Total Air flow} \times 1.085 \times \text{Delta } T \text{ airside} \quad \text{sensible space heat load} \\
\text{Total OA loads} = \text{Total Air Flow} \times 4.5 \times \text{refers to outside air load} \\
\text{Total tons} = \text{Total OA Load} / 12000 \\
\text{TONS/FAR} = \text{Total tons} / 12000 \text{ sq ft}
\]

² Enthalpy is understood as the total amount of heat in one pound of a substance calculated from accepted temperature, expressed in BTU's per pound mass (Btu/Lb).
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Air handler size = Total Air flow/ 500 (HVAC industry standard)
VFD air handler Size = Total Air Flow/ VFD speed

6.2. Deriving information required for cooling load calculations

For the calculation of the cooling loads required by the FDA-PCD tool, is critical the clear identification of the internal heat loads of each of the spaces in the building model, in the case of laboratory spaces, laboratory equipment is the main contributor to the internal loads; NIH recommends 7.9 w/sq ft to represent heat gains during PCD; the ASHRAE handbook recommends values ranging from 5 to 25 w/sq ft the latter for highly automated laboratories. Brown [17] indicates laboratory space equipment loads variations from 5.0 to 26 W/sq ft with an average of 12.3 w/sq ft; this is the value implemented for PCD, this is done having in mind that, the real equipment specification for each of the laboratory spaces will occur at later stages of design. Office space heat loads are mainly generated by the number of occupants and the tasks lights associated with them, we have embedded in the Office Schedule a heat load calculation per each space instance, this uses the recommended values for room lighting of 1.3 w/sq ft [3, 4], 250 watts load per occupant task light, and the occupant itself with 115 watts each [16]. These will help AE’s to verify the heat load of building wings containing office spaces or to obtain the average for multiple office instances needing to be grouped in a department. In the case of circulation areas the internal heat load is mostly generated by room lighting, for the purpose of PCD heat load computations and because of its similar configuration we use the ASHRAE recommended value for Hospital facilities, which is 1.0 w/sq ft [16].

Another input required by the FDA-PCD tool for the computation of cooling loads is enthalpy; this represents the heat content of the air mixture. It is required for AE’s to provide; firstly "h in" which represents the enthalpy of the air coming from the exterior of the building; Secondly "h out" representing the conditions required in the serviced spaces. In order to derive the enthalpy values required AE’s need to consult a psychometric chart (Figure 18); this depicts the physical properties of moist air at a constant pressure usually at sea level, the parameters in the chart are: Dry-bulb temperature, Wet-bulb temperature, Dew point temperature, Relative humidity, Humidity ratio, Specific volume, and Specific enthalpy. In order to obtain the required data from the Psychometric chart, AE’s needs to know at least two of the previously mentioned parameters. The rest of the parameters can be obtained by following the intercepts in the chart as shown in Figure 18, here by knowing the dry bulb temperature value (85 F) and the humidity ratio (0.0085) we can derive the value for enthalpy of 30 Btu per Pound.

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3 The previous formulas are of common use in HVAC cooling load calculation and can be found in a variety of sources [10, 11].

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Fig. 18. Psychometric chart used to derive physical properties of humid air. Based on the mathematical formulas presented in Rational Psychometric Formulae 1911 by Willis H. Carrier.

Because of the strict control of the environmental conditions inside of laboratory buildings, parameters regarding both the required temperature and relative humidity are usually defined in design guidelines for laboratory buildings, such as table 1 of this document [4]. Data regarding the environmental conditions outside of the building can be found in the National Weather Service [12].

Table 1. Indoor design conditions, NIH design policies and guidelines, Office of Research Facilities/ National Institutes of Health, Department of Health and Human Services USA. 2003

<table>
<thead>
<tr>
<th>SEASON</th>
<th>TEMPERATURE (°C)</th>
<th>HUMIDITY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>73,4 ± 1,8</td>
<td>50 ± 5 relative humidity</td>
</tr>
</tbody>
</table>
6.3. **Implementing the Velocity Face Drop utility in the FDA-PCD tool**

Ventilation can account for up to 50% of the energy consumption in laboratories [18], traditional calculations of air handlers are based on a face velocity of 500 feet per minute (FTM), this industry standard was never intended to be applied in equipment needing to work uninterrupted as in the case of laboratories. The implementation of Face Velocity Drop (FVD) is directly connected to reductions in the air handler fan power requirements, for instance "a 25% of reductions of the velocity face speed yield a 40% of reduction in power requirement"[18], case studies report a 30% to 50% less energy consumption compared to a constant volume (CV) system [19]. Weale, Rumsey, Sartor, Lock, and Lee [18] report gains in efficiency for VFD values of 400 and 300 FTM, The FDA-PCD tool base line load schedule provides AE’s with the possibility of exploring multiple configurations for the ventilation systems, in its default setting the tool calculates the size of required air handler unit per each HVAC zone using the CV of 500 FTM, but it allows designers to verify the results of applying VFD by inputting a "VFD speed" value and calculating the "VFD air handler size" for each of the HVAC zones.

7. **Summary**

The implementation efforts summarized here have been carried as to better understand the capabilities of BIM applications to provide design assessment through their default interfaces. We have analyzed the capabilities of relational views to the BIM data base and parametric object families as capable of supporting the implementation of PCD assessment regarding both parametric behavior and feedback capabilities. It has been demonstrated here that information contained in BIM data structures can potentially serve to automate generative based design assessment without the need for developing plug ins or exporting the data to external applications, which can be both economically expensive and time consuming.

The same way as with other methods to embed expertise in to computational systems [6] the tool described here has been customized for its application on a specific building type and to operate with specific levels of building model semantics, but is easy to see that similar approaches can be used to assess different building types and a wider range of assessments.

Among the limitations found in this study, is that of the impossibility of assessing space to space relationships, limiting therefore the possibilities for assessing space adjacencies which might be valuable for the spatial lay out
analysis, the assessment capabilities demonstrated here are mostly based on the predefined relational views of the native BIM data structure which are mostly at the level of object types, and are intended to be implemented by BIM users. Complex operations can be implemented through the use of application programming interfaces, which are available for most contemporary BIM applications. But this limits their usability to expert programmer, which is not the intention of this study. Complex assessment can be achieved upon generation of assessment specific representations, but these require implementation of specific data structures designed for the sole purpose of design assessment and require either the development of an application programming interface or the use of external applications capable of both reading BIM data and to construct assessment specific data structures. Although extensive evaluations of the FDA-PCD have been completed by the implementers, the user validation has been limited to practical demonstrations and remains as a key issue for future developments of the tool.

Issues such as; modeling practices, availability of the model semantics to support assessment, and the required user expertise for implementing automated design assessment are still issues to be addressed if a broader use of these technologies is to be accomplished.

References

3. NIH design policies and guidelines, Office of Research Facilities/ National Institutes of Health, Department of Health and Human Services USA, 2003.