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# BIM Based Normative Calculations for Early Stages of Building Design

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**Abstract** This paper describes research developed in automatic of normative calculations using BIM technologies for the purpose of supporting design decisions based in engineering data, such systems are an important design assessment parameter when performing design decisions, and influence in the performance of the building in early stages of design. Our research concentrates in developing computational technologies to allow computer software to implement normative calculation to support designer's capabilities to perform design decisions, this is done in the domain of ventilation systems engineering. We describe here new methodologies for embedding engineering domain heuristics normative calculations and the associated geometric operations in contemporary Computer Aided Design (CAD) software; this is done to achieve close to real time engineering feedback, therefore, facilitating engineering base decision making during early concept architectural design workflows. This research has been developed in the context of laboratory buildings, since for these there is several well-established normative calculations regarding both design best practices and systems engineering particularly in Heating Ventilation and Air Conditioning (HVAC), particularly in ventilation.

***Keywords:*** *BIM, building performance simulation, early concept design, HVAC*

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## 1. Introduction

The correct design of the ventilation systems in laboratories applies not only to the environmental conditions inside the facility, also the airflow patterns designed for laboratories determine the security conditions for building occupants and given the operational requirements of 24 hours a day 7 days a week for these types of systems, the operation of ventilation systems can account for about 50% of the energy usage of the facility [1]. Ventilation systems engineering is intrinsically connected to the design of laboratories, different types of this knowledge is applied at almost every step of the design process from Pre- liminary Concept Design (PCD) to Design Development (DD). Even though collaboration between architects and engineers is a common practice in later stages of design, this has not been the case for PCD workflows, this is mainly the result of the speed in which design alternatives are produced during PCD, the complexity of traditional HVAC simulation tools, and the fact that most of these require complex data modeling before any feedback can be pro- vided to designers [2]. Design decisions taken during PCD can affect the performance of laboratory facilities and the ventilation system itself, most of the time these are made mainly by the architectural designer, and when a design decision is based on ventilation engineering is based on non-rigorous rules of thumb. We will explore in this thesis how to automate normative calculations and improve on what is considered traditional practices in the estimation of ventilation systems engineering during PCD, and how normative based engineering feedback involved in these practices can be produced by a domain specific Building Information Modeling (BIM) based computer software. For this purpose, we developed a software prototype named Laboratory Ventilation Design Assistance (LVDA) which is designed to be used by both architects when evaluating the PCD of ventilation systems engineering of laboratories.

## 2. Methodology

This research is based on an extensive literature review dealing with the design and engineering of ventilation systems for laboratories. We investigate here the domain expert knowledge used for ventilation systems engineering in laboratories and the development of new approaches for computational support of these. We have compiled domain expert knowledge in the form of best practices, compliance codes and industry standards in the laboratory design domain. With the knowledge acquired we have developed prototype computer software called LVDA. We evaluate the capabilities of the prototype contrasting its performance to commonly accepted computational tools for the engineering of ventilation systems. Research

Motivation Currently there is lack of computational support for close to real time engineering of ventilation systems in early stages of design. This lack of computational sup- port becomes even more critical in very early stage of design, where design decisions happen at a very fast pace, revisions are less costly and design decisions have big impact on building performance. The estimation of ventilation systems engineering can help designers to improve the overall performance of the facility by optimizing the design in regards of the ventilation system, which in some cases can account for about 50% of the electrical consumption of the facility [1]. The importance of ventilation systems engineering in laboratories commonly known as ventilation driven facilities, laboratories demand higher number of air exchanges than other building types and well-planned directional air flows [3,4,5], this becomes of extreme importance when dealing with high levels of Biosafety Level (BL) laboratory spaces. Also, laboratories require 100% fresh since their equipment exhaust cannot be recirculated, therefore more air needs to bring into the building to make up for the exhaust. These requirements translate to higher energy consumption. Also, the design of the air distribution network in a laboratory is commonly considered an environmental safety measure, since is designed to reduce the possibility of cross contamination within the facility in case of a chemical spill. The directional airflow patterns in laboratory layouts are designed to be negative towards all laboratory spaces. In traditional practice the design of the directional airflow structure is made explicit on floor plans by placing arrows pointing the direction of the flow along with the flow rate, please see Figure 1.

Traditional practices in the design of directional air flow networks have been usually based on the pressure differential between adjacent spaces, this type of structure is commonly constructed by increasing the amount of air flow exhaust within the laboratory spaces [6,7], thus increasing the energy consumption of the facility. Another approach would be, by tightly sealing the laboratory doors; however, this is not particularly efficient when doors are opened by users [7]. Bennet [7] pointed that inward air flow can be more accurate for controlling the air flow patterns between two adjacent spaces.

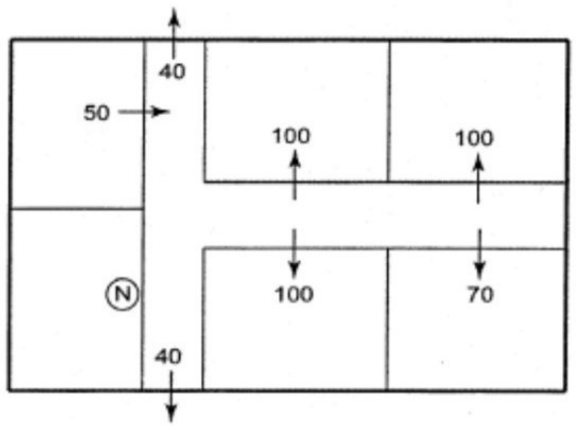



**Figure 1.** Directional air flow mapping in cubic feet per minute

The design of the inward based directional air flows is directly connected to the spatial adjacency structures of the layout and the air pressurization of the different spaces in it, making it a valid approach for the development of architectural design assistances since most of these are commonly based on the spatial properties of the layout. The spatial arrangement of the layout defined by the architect also affects the performance of the ventilation system regarding the required air pressure of the ventilation branches. The locations of served spaces within the layout and the typology of layout have direct impact in both the length and the number of turns that the ventilation branches must have to reach all the required spaces. Domain expert groups (Labs21, NIH, ASHRAE, and LBNL) have recently emphasized the need for incorporating HVAC engineering, and therefore ventilation system engineering, throughout the design process of laboratories, including early phases. But it is hard to think of having the HVAC engineer along with the architect while the development of the PCD occurs or for the architect stopping the design workflow for hours waiting for the engineer to provide feedback.

## 3. Domain of Implementation

The level of design abstraction of a project might not be critical when dealing with paper-based representations, but it becomes extremely relevant when the design representation is constructed as a computational model with the purpose of supporting design assessment. Although there is not a widely adopted standard for the level of completeness of computational models in architecture and engineering (AE), recent efforts have tried to define the different levels of design development for computational models [8,9]. Among these the General Services Administration, Facilities Standards for the Public Building Service (P100) clearly establishes standards for new buildings, among these it defines the levels of design development as: Preliminary Concept Design (PCD), Late Concept Design (LCD), Concept Design (CD), and Design Development (DD). In it, the semantic content for each of these is clearly defined making it suitable for the research developed here. In the P100 PCD projects are defined in terms of the content as follows: placement and massing of the building are defined; program spaces are identified only at a departmental level, circulation spaces both human and vehicular are identified, no internal partition walls or wall openings, basic definition of building boundary surfaces. 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. Few objects usually are included in PCD BIM models besides space objects; among these; building envelope needs to be identified, partitions among spaces are represented either with wall objects or virtual walls. These PCD BIM models are usually developed for the purpose of massing and layout studies. In the case of laboratory buildings, the main spatial referent for spatial layout programming is the laboratory module. The sizing of laboratory modules allows AE's to define the PCD layout of the building's structural grid, and to have a clear approximation to the expected occupancy loads of the facility.

The PCD of laboratories and engineering assessment In PCD of laboratories, there is no precise framework for how engineering expertise is brought in to PCD, most of the time engineers will get involved once the massing of the building and the internal layout has been completed by the architect. Often the PCD architecture tends to optimize the spatial adjacency of the facility in terms of spatial relationships or functional requirements, but in terms of ventilation engineering there is no specific optimization but the application of engineering knowledge at the level of rules of thumb regarding the floor-to-floor clearance required building systems [10]. In traditional laboratories PCD, after the model is completed by the architect, is handed to the engineer who will extract its geometric properties, add to it his or her expertise in code requirements and best practices to produce a ventilation engineering data model. Then after the cooling loads have been estimated the results are returned to the architect, who based on the results might explore design alternatives. If new alternatives are explored by the architect, a new cycle of engineering estimation is conducted. The overall time required for each of these iterations might be hours in the best of cases. After analyzing the BPM, please see Figure 2, is easy to infer the reasons for inefficiencies in the process, only in data exchanges/inputs, there are at least 9 steps, even more; some of these exchanges rely on manual extraction/manipulation of data. Therefore, they are susceptible to error.

## 3.1. BPS Integration to Laboratory Design Processes

In general terms Ventilation system design using BPS's is usually performed after the spatial arrangement of the facility is consolidated, and the material specification and configuration of the building envelope is well known by the design team. In traditional building design practices is during CD or FCD when the HVAC engineer will conduct a detailed analysis of the heat loads in the facility, define the ventilation rates per space, determine the airflows, and propose the duct layout including the location of vertical drops as well as pieces of equipment. The results of the CD or FCD HVAC engineering analysis can generate a set of design revisions to properly fit the HVAC components and their requirements [11,12] which due to the state of completeness of the design might produce costly revisions and time delays.

The previously described process is supported using BPS by the building design team, many of these tool's features make it hard for any implementation of collaborative design environments in early stages of design [1]. Some efforts have been made to automate some areas of the BPS process to make them more suitable to early stages of design, still many of these require for a certain level of semantic content in the PCD model, such is the case of material definition for walls, and sizing and placement of doors and windows. This content, usually available in CD or FCD is not commonly part of the design semantics of PCD. Other reasons can also be pointed as to why BPS's are not suitable for PCD such as; the speed in which the design changes happen during this phase [13], the time required to prepare and complete BPS, among others clearly limits the application of these, since once the BPS has been completed the design might have changed making the analysis results obsolete [2]. Both Holzer [13] and Chaszar [14] indicate that software's results might not enable interdisciplinary collaboration and that different domain semantics can create friction within design teams. Holzer [13] also points among the issues limiting the interdisciplinary collaboration, the need for team members to reflect in privacy regarding the proposed solutions.

## 3.2. Current Trends in Engineering Assistances

The development of computational BPS tools has been going on for over 40 years. The range of these varies from; excel based to special purpose highly advanced software. Trˇcka and Hensen [15] identify three generations of BPSs; the first was based on analytical formulations and simplified assumptions, the second one based on numerical methods, and provided partial integration of performance aspects of buildings, the current generation of BPS can capture reality better and are fully integrated regarding different performance aspects. In the area of HVAC there are roughly four categories of BPS's, these are based in the problem they are trying to analyze:

- Equipment sizing: Carrier HAP, Trane Trace, Energy Plus, Design- Builder, MC4suite etc.
- Energy performance: Carrier HAP, Trane Trace, Energy Plus, DOE-2, Equest, ESP-R, IDA ICE, Trnsys, Hvacsim+, VA114, Simbad, Building Energy Analyzer, DesignBuilder, etc.
- System optimization & controls: Genopt (generic), Contam, Energy Plus, ESP-R, Trnsys, Dymola, etc.
- Duct sizing: AFT Fathom, Dolphin, Duct Calculator, Duct size, Pipe- Flo, Python, Indus, Cymap, etc.

Sources: http://apps1.eere.energy.gov/buildings/tools directory/subjects_sub.cfm, Trˇcka and Hensen [15].

Most of the previously listed have been developed for the purpose of HVAC engineering design; therefore, they require the construction of highly specialized domain specific data models, with properties, such as; transmittance values, operating schedules, equipment types, control strategies, and utility rates. Many of these have complex UI's, and the feedback produced might be hard to understand by non-domain experts [16]. Current efforts in BPS development concentrate on improving the integration of these to the overall building design process [17]. In this context three main areas are being researched: the simplification of either the calculations being performed [18], the simplification of the simulation data model being used, and the automating generation of simulation models for the execution of BPS [19,20]. This research takes on these trends and goes a step further in the effort of integration to design process by embedding engineering estimation within BIM CAD software.

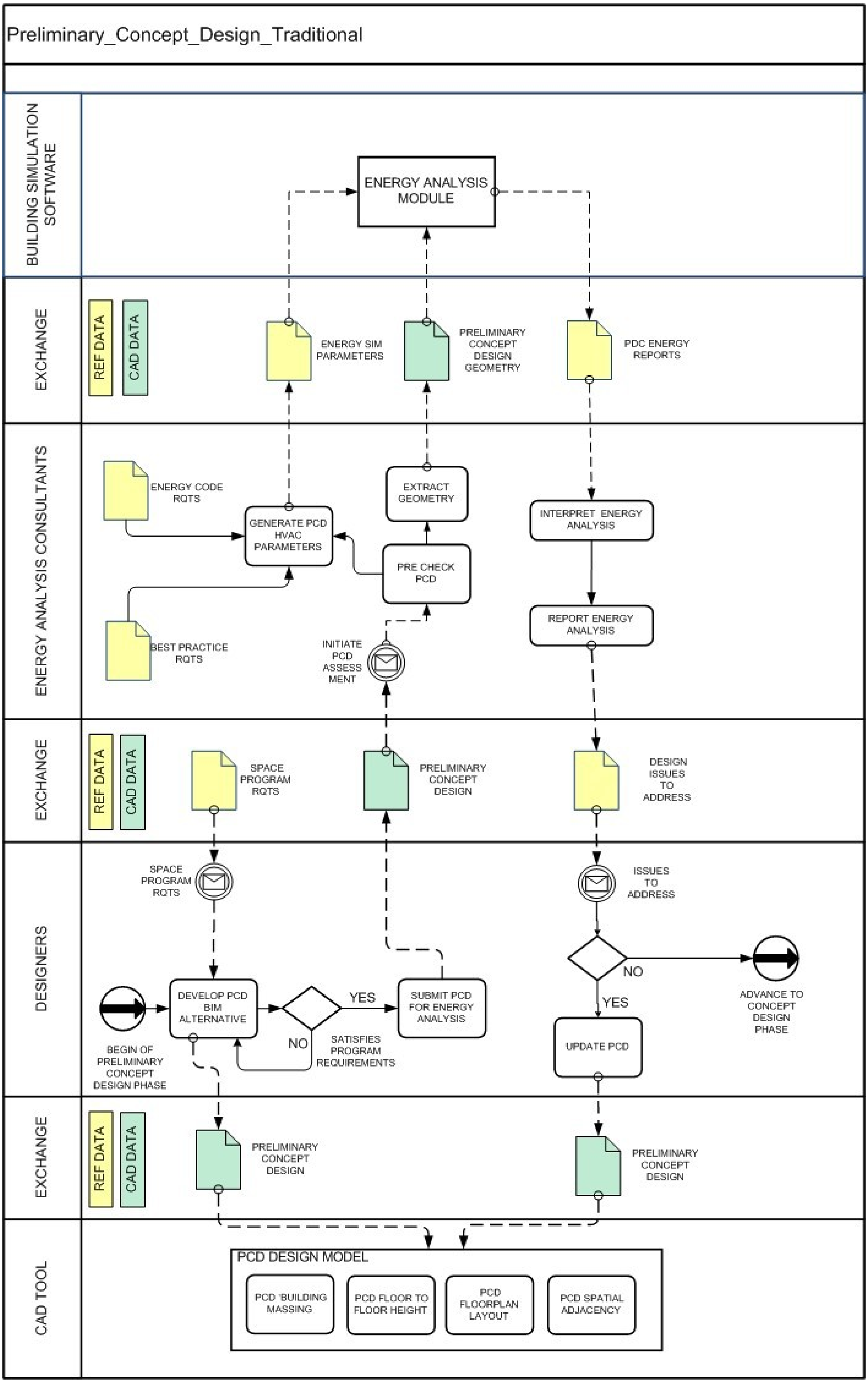



**Figure 2.** Business Process Model of traditional PCD of laboratories (author)

## 4. Methodology for Acquiring and Implementing Ventilation Systems Engineering in Laboratories

We have conducted an extensive research dealing with widely recognized compilations of best practices and normative calculations applied to the engineering of ventilation systems in laboratory design, these range from energy standards [21], design requirements [4], design guidelines [3,5,22,23,24], and HVAC engineering [25,26]. From these we have extracted provisions dealing with the following issues regarding engineering of ventilation systems in the following areas: Recommended design practices in terms of operational procedures Normative calculations for code compliance Code compliance for the design of ventilation systems Minimum ventilation requirements for the operation of the facility Best practices for the safety conditions for the facility Systems serviceability provisions In order to enable the implementation of these in computational form, each of the provisions extracted was categorized as follows: Formulaic Normative data: this refers to algebraic computations required for the engineering of ventilation systems in laboratories e.g. "cooling loads calculation" (equations 1 to 6).

$$Delta\ h = h\ in - h\ out \tag{1}$$

Where:
h in = enthalpy in (Btu/Lb)
h out = enthalpy out (Btu/Lb)

$$Delta\ T\ airside = LAT - EAT \tag{2}$$

Where:
EAT = entering air temp (Fahrenheit)
LAT = leaving air temp (Fahrenheit)

$$Total\ Air\ flow = Load \cdot 3.41 \cdot \frac{Area}{(1.09 \cdot Delta\ T\ Airside)} \tag{3}$$

$$Sensible\ heat = Total\ Air\ \ flow * 1.085 * Delta\ T\ airside \tag{4}$$

$$Total\ OA\ loads = Total\ Air\ Flow * 4.5 \tag{5}$$

$$Total\ tons = \frac{Total\ OA\ Load}{1200} \tag{6}$$

Note: The previous formulas are of common use in HVAC cooling load calculation [25], Engineer toolbox web site (https://www.engineeringtoolbox.com/).

Domain expert knowledge: this refers to explicit information that is used during the engineering of laboratories ventilation systems, which is not algebraic in nature E.g., "temperature-controlled rooms shall be lockable, and all mechanical components shall be accessible and serviceable form outside the room" [5]. In many cases the computational implementation of ventilation system engineering requires from a combination of both types of knowledge, this was articulated by the creation of an algorithmic interpretation layer within the overall research structure..

### 4.1. Capturing Formulaic Normative and Domain Expert Data

The forms method- ologies for capturing knowledge vary depending on the area of expertise being processed. For instance, in some areas of architecture design it might be the size of service areas in a building regarding the usable square footage of the layout, in engineering design it might be the types of connectivity that a pre- cast concrete beam needs to have when installed under conditions, or it might be the result of a combination of multiple forms of expertise data which when combined represent complicated areas of design knowledge [6]. In the case of ventilation engineering for laboratories, the expertise data is in most cases based on the relation between the space usage and the attributes of the space instance in terms of environmental requirements, scientific processes, internal equipment, or mechanical systems requirements. Engineering ventilation expertise also has a relation to the facility layout and spatial adjacencies defined in it, since these impacts both the safety conditions of the building and the efficiency of the systems.

#### 4.1.1. Capturing Formulaic Data

Collected in the form of algebras related to either the application of semantic based knowledge or parameter processing for assessment engineering data computation, two types of formulaic data have been Identified, space-based formulas, environmental conditions formulas. Capturing semantic data: collected at the level of space types and their specific attributes regarding environmental requirements, also ventilation system components their properties and performance characteristics. Two types of collections have been defined for semantic data: type's classifications, and provision behavior. Documentation and interpretation of semantic types in this research we define both ventilation components classifications (Table 2 recommended duct sizing, Table 3 minor loss coefficient for common duct components), and space instance classifications which includes all those spaces commonly used for the programming of laboratories. The ventilation component classification has been hard coded in to the LVDA to avoid any kind of erroneous manipulations which might reduce the accuracy of the prototype software. The space instance classification has been collected in a human readable input file to support customization and application to other building types. The input file developed for the LVDA incorporates the following space types:

- General chemistry
- Radio chemistry
- Research
- Hospital or clinical
- Biological containment
- Animal research
- Isolation/clean rooms
- Materials testing
- Electronics/instrumentation
- Teaching

- Laboratory Support
- Offices
- Toilet
- Lockers/showers
- Conference/ Break rooms
- Corridor
- Service Corridor
- Elevators
- Loading docks
- Housekeeping closets
- Mechanical, electrical, and telecommunication
- Service Shaft
- Interstitial Space
- Stairs

Each of these is explicitly space types is associated to a set of space at- tributes or properties; these along with their values have been compiled from domain specific guidelines [3,4,5,22,23,24]. When processed by the system these attributes are embedded by the LVDA in the BIM project database, therefore, enhancing the semantics of the BIM model to both; sup- port LVDA proprietary computations, and other types of BPS assessment that might happen downstream in the design process. The attributes embedded take as reference those identified in the indoor climate simulation to HVAC design model view definition, developed by Voulle, Hanninen, Berard, and Lehtinnen.

## 4.2. Documenting and Interpreting Provisions Behavoir

In this research we have documented provisions behavior directly into the algorithms composing the LVDA prototype, it is understood here that the capability capabilities of decision, computational decision trees available in computational algorithms suits well the translation of provisions behavior E.g., “temperature-controlled rooms shall be lockable, and all mechanical components shall be accessible and serviceable form outside the room” [5]. In this example, the provision is translated to an algorithm that estimates the ventilation system routing and constraints the geometry of the route, so it never passes through a serviced space to supply another serviced room, the described provision behavior is implemented in the LVDA Ventilation Routing Estimator Module (VREM).

### 4.2.1. Implementation Technologies

For the implementation of the LVDA two pieces of contemporary technologies have been selected; Firstly, the rich objects semantics provided by BIM data bases; Secondly, the estimation of engineering data using normative calculations in- stead of traditional BPS approaches. Lee and Eastman [27], demonstrated how semantically rich BIM environments found in BIM can be used for the derivation of spatial relationships embedded in the building design. Their research also enhanced the decision process of very early stages of design by operating within the reduced semantics typical of these, their assessment structure was based on a standalone rule-based BIM checker software. Park and Augenbroe [28,29] demonstrated the viability of using normative calculations for energy consumption estimation; they also pointed that normative calculations are well suited for sensitivity/feasibility studies for buildings in design stages. Although Park [29] point that normative calculation’s approach for energy consumption, might not be suitable for ventilation driven facilities, this thesis proposes the use of simplified calculations derived from well-established HVAC engineering practices [3,30,31,32] to be used for the estimation of engineering ventilation systems.

# 5. Implementation of the LVDA

The During the early stages of this research it was identified the need for the LVDA prototype has been designed to provide close to real time user feedback with a limited number of inputs, and to structure the system operation to suit the characteristics of embed itself as well as possible to laboratory PCD workflows. Based on these principles, the system has been organized in to two stages functionality, that controls which in turn control the execution of four operational modules. The first stage; the cooling load calculation triggers three different routines: dynamic heuristics assignment, cooling load calculator, and the environmental information retriever. The second stage; the airflow estimator triggers: the air pressure structure analyzer, the routing estimator, and the airflow calculator. Another aspect identified early in the development of the LVDA was the necessity for it not to disrupt the flow of the design process. For this reason, instead of developing a standalone application, all the modules of the LVDA have been embedded in the back end of a CAD BIM software in the form of plug-in software. Most contemporary BIM software’s can extend their operational capabilities, through what is called an Application Programming Interface (API). These allow computer programmers to connect their own software to the internal operations of other software’s. This structure supports the development of specialized functions utilizing using both the default capabilities of the BIM and the data base of in it. Different BIM applications support the use of a variety of programing languages in their API’s. The detail of the programing languages supported by BIM software’s currently available in the USA is as follows (Table 1):

**Table 1. Architecture Design BIM software, API language interface**

| Software | Supported programing language |
|---|---|
| Autodesk Revit | VB.NET, C#, C++ |
| Graphisoft Archicad | C, C++ |
| Bentley Microstation | VBA, C#, VB.NET |
| Nemetscheck Vectorworks | C++ |
| Gehry technologies Digital Project5 | VBA, VB.NET |

The LVDA prototype has been implemented in Autodesk Revit. This has been chosen because of its popularity, almost 70% of the market in the US uses it [33], and because it’s API supports the use of several programing languages, among the available ones we have chosen C#. Although the LVDA prototype implementation has been done using C#, and using Autodesk Revit specific functions, high level pseudoalgorithm is also provided here to support the application and reuse of the knowledge developed here into different programming languages and other BIM platforms. The user interface designed for the LVDA, please see Figure 3, is based on the concept of simplicity; therefore, it requires from end users the least possible number of inputs. There are only two buttons in the LVDA interface. These two are constructed in the Revit Ribbon panel. Within the LVDA system architecture, these two modules take on the responsibility of controlling the execution of all other modules in the LVDA. If data needs to by dynamically loaded into the system users might be required to act, such as to point the location an input file or connect the computer to the World Wide Web for the acquisition of weather data.

### 5.1. Development of the Heal Load Calculator Module (HLCM)

The Heat Load Calculation Module (HLCM) it was the LVDA module developed to replicate the ventilation system engineering traditionally available within the context of PCD of laboratories. It appears in the UI as Building Cooling Loads. In traditional PCD workflows, after the massing and the interior outline of the laboratory building is laid by the designer, the HVAC engineer proceeds to extract the geometric data contained in the design and calculates the cooling loads for the entire facility, please see Figure 2. Heat load calculation Module (HLCM) Given the nature of the LVDA prototype, all the operations defined for the ventilation system estimation are based on traditional engineering feedback for PCD, in this context the HLCM oversees performing the estimation of the cooling loads, this is done by calculating the internal heat gains of each space instance, this is done based on the space usage and the values for heat loads defined in the LVDA input file, these have been extracted from code compliance standards but also can be modified by the end user if necessary. The HLCM controls the execution structure for other modules in the LVDA, it controls the data transactions with the BIM data base and the UI interactions, these include system warnings, request for actions, design feedback.

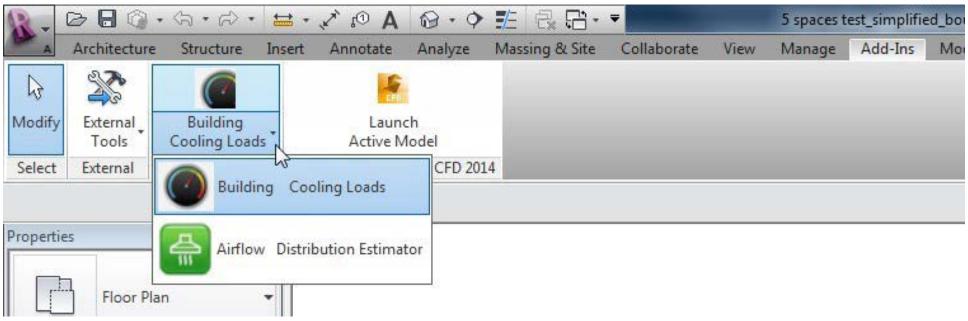



**Figure 3**. LVDA user interface

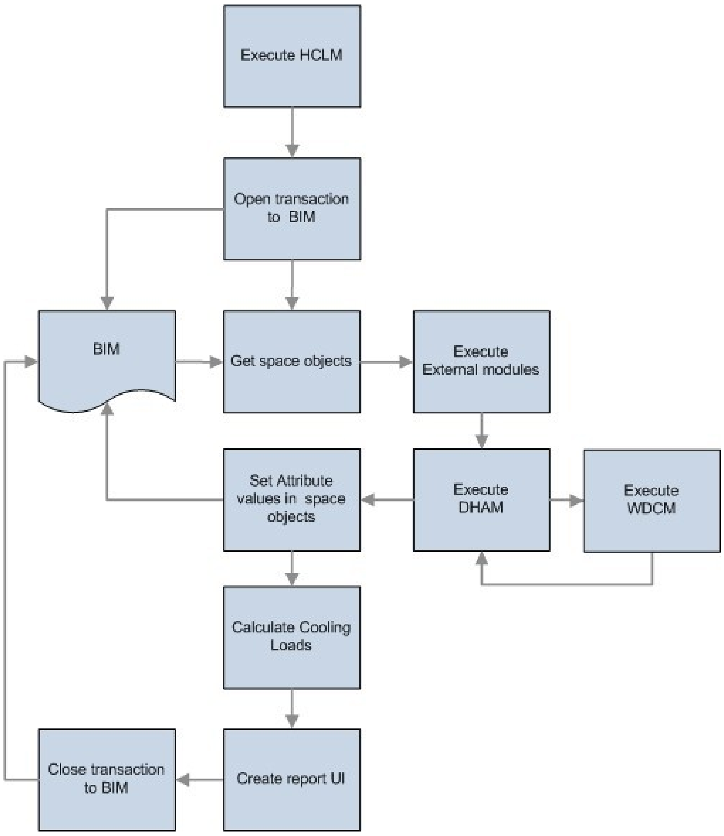



**Figure 4**. HLCM Flow chart

The runtime workflow of the HLCM has been constructed using the following workflow (Figure 4), the HLCM functions as a container for both the Dynamic Heuristics Assignment Module (DHAM) and the Weather Data Calculator Module (WDCM). The reason for this architecture is because; the outputs of these two modules are required by the HLCM to compute the cooling loads and to generate the required engineering estimation feedback.

The HLCM controls the data transactions with the BIM application and, the execution structure for its own routines and the modules being called by it. During runtime, the first step of the HLCM execution verifies the existence of a parameters group within the BIM project data base, the "LVDA HVAC data" the existence of this parameter group indicates to the HLCM if the LVDA has been used in this specific project on a previous de- sign session. The absence of the group indicates the need for these to be to be created. If this parameter group does not exist, the execution is passed to the Dynamic heuristics Assignment Module (DHAM). Then and after all the DHAM operations are completed the HLCM creates the feedback interface and constructs the different levels of data aggregation for the feedback to be displayed. For the delivery of the design feedback, we use one of Revit's traditional feedback structures; Schedules, these are text-based representations of BIM data, please see Figure 5, therefore there is no need for opening a different application to evaluate the status of the design, just the need to navigate within the same environment.

The schedule generated by the HLCM (Figure 5), provides different levels of data aggregation for the ventilation engineering data; space instance cooling load, and building level aggregation of the overall cooling load is provided at the bottom of schedule. implementation strategy the following algorithm structure provides a high-level representation of the HLCM implementation and its logical structure, although the prototype of the LVDA prototype and by aggregation the HLCM have been developed using C#.

In different design phases and particularly in PCD it is hard to assume the BIM will have a certain level of completion when evaluated or operated on by computational systems i.e. It might well be the case that either the model contains all the spaces required in the program or that it only contains departmental level aggregation of functional spaces. To face this type of modeling issues; the mapping structure of the HLCM looks for all the space names defined in the LVDA input file, and then maps them to the space objects in the BIM. This means that there a high level of control over the scalability of the software operation and the parameter values associated to each space type, since the input file can contain a variety of programmatic spaces ranging from departmental level aggregations to single program spaces high levels of detail containing all the required space types. The only data fields which are constrained in the HLCM mapping structure engine are the parameter names and the types associated to each space usage instance; this is done as a mechanism to keep control over the accuracy of the computations implemented.

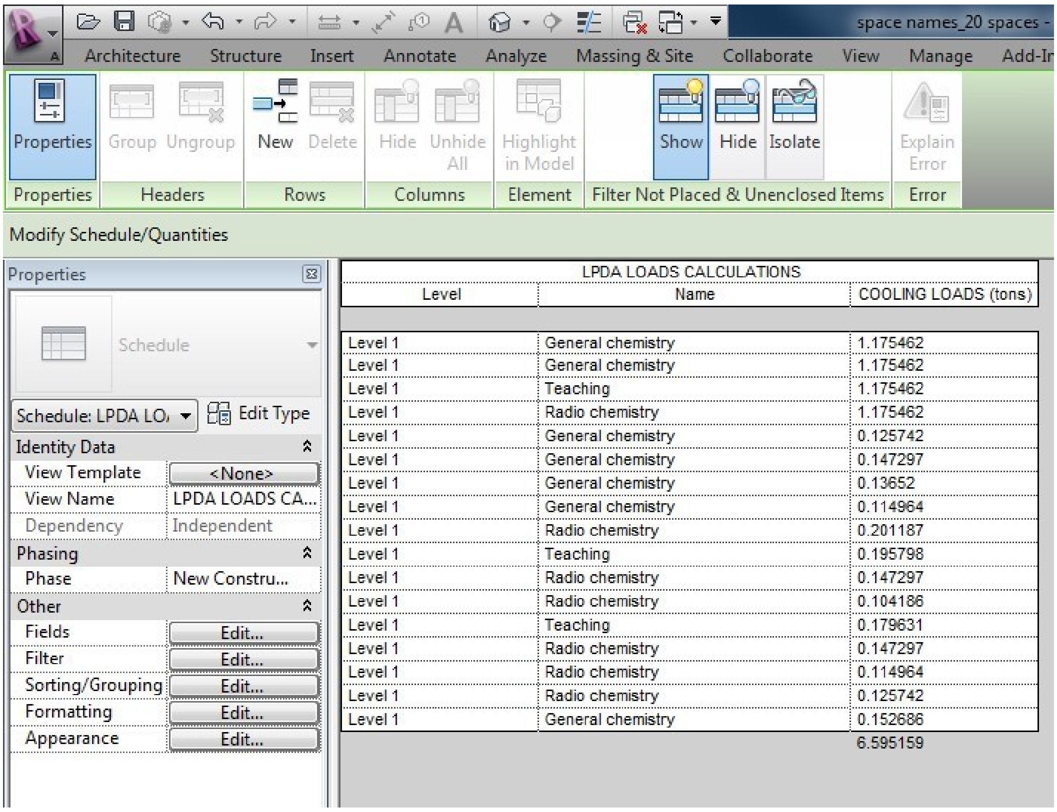



**Figure 5.** LVDA Cooling Load feedback

## 5.2. Development of the Weather Data Calculation Module (WDCM)

The other piece of software which is important for the overall operation of the HLCM is the retrieval of the building's location and its weather data. In traditional process this is provided by the engineer as text information. For the BIM enabled energy engineering estimation there is the need of automatically retrieving these and to embed those in the project data base for its reuse downstream the design process. In the LVDA this operation is assigned to the WDCM Weather Data Calculator Module (WDCM) During the development of the WDCM, it has been assumed that; it would be hard for designers to provide detailed weather data before the execution of the LVDA. Therefore, the WDCM has the capability of retrieving it from external sources and place within the BIM data base. Unlike traditional BPS where in some cases users need to manually load the weather data files, or to explicitly identify the project location, the WDCM calls the active Revit Document, and looks for the project in- formation property, particularly the address string. If this attribute is not located; the WDCM triggers a UI pop up window requesting the user to provide the city in which the project is located, please see Figure 6. After the string for the location has been provided the WDCM will place it in the doc. Project Information. Address location of the active project data base. Then the WDCM using the building location data and the .net framework capabilities, calls the national weather service though an available network connection, access the weather files database and retrieves the weather data file for the required location. Once the weather file has been parsed by the WDCM, instead of using data values for each of the time steps available, the way a traditional BPS would do, the WDCM extracts and averages the data to perform the computations of cooling loads [34,35] The operational structure of the WDCM is described in Figure 7.

## 5.3. High Level Algorithm and Implementation Strategy

The WDCM algorithm structure provides a high-level description of the implementation of the WDCM and its logical structure, although the prototype of the LVDA and the WDCM have been developed using C#, Enthalpy Calculator Module (ECM) One critical piece of data required by the WDCM to calculate the cooling loads of each space object is the value of enthalpy. Enthalpy is under- stood as the total amount of energy in a substance, in this case air. In the context of ventilation systems engineering enthalpy needs to be calculated for both the building location and each of the spaces in the BIM project.

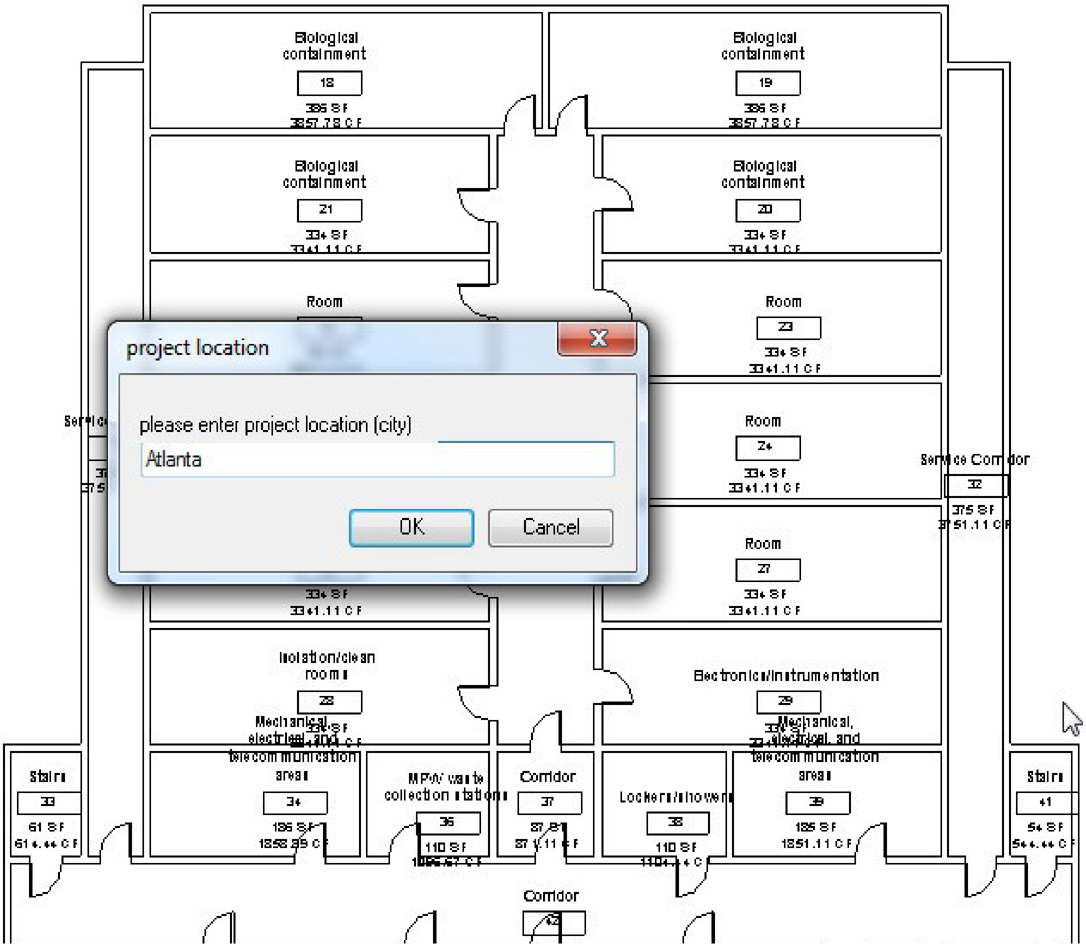



**Figure 6**. WDCM user interface, project location window

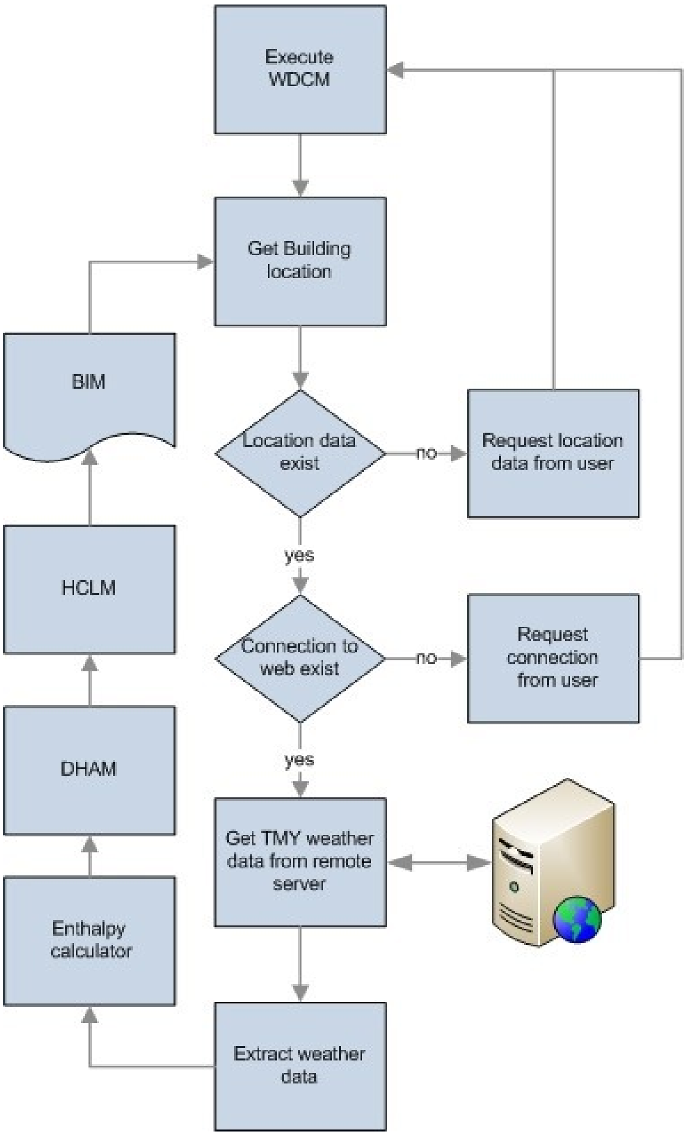



**Figure 7.** WDCM Flow chart

In traditional PCD this is commonly calculated by the HVAC engineer after the designer has completed, he/she computes the enthalpy by extracting values from a psychometric chart based on the elevation of the building site regarding the sea level. For the automation of the calculation for enthalpy values, instead of requesting users for environmental information or loading and extensive data base which would slow down the process. we have developed for the LVDA prototype, the automated computation of enthalpy values through the ECM.

## 5.4. ECM General Level Algorithm

The implementation of the ECM is based on the application of mathematical formulas formulaic data for the computation of both enthalpy and humidity ratios in the domain of HVAC engineering. The formulas implemented in the ECM are expressed as follows:

$$h = ha + x\,hw \tag{7}$$

Where:
h = specific enthalpy of moist air (Btu/lb)
ha = specific enthalpy of dry air (Btu/lb)
x = humidity ratio (lb/lb)
hw = specific enthalpy of water vapor (Btu/lb)

The calculation of humidity ratio can be expressed as:

$$x = \frac{0.62198\,pw}{(pa - pw)} \tag{8}$$

Where:
$p_w$ = partial pressure of water vapor in moist air (psi)
$p_a$ = atmospheric pressure of moist air (psi)

The ECM uses the following input values for the calculation of enthalpy:

- Maximum temperature
- Atmospheric pressure

These are extracted from both the weather data associated to the building location and each of the space instances in the BIM and their functional normative requirements as defined in the LVDA input file.

## 5.5. Implementation Structure of the ECM

The computation of enthalpy is per-formed both for the building location and for each of the space objects in the BIM. Only two pieces of data are retrieved by the ECM from either the space object or the building location, these are the temperature and atmospheric pressure. The workflow of the ECM is as follows.

#### 5.5.1. Development of the Dynamic Heuristics Assignment Module (DHAM)

The DHAM was designed to automatically enhance the semantic content of the BIM to allow for other LVDA modules in the LVDA prototype to perform their computations. It operates by associating HVAC engineering domain heuristics and normative data to the object's attributes in the BIM data base. Defining automated heuristic inputs for enhanced data models the type of ventilation engineering assessment performed by the LVDA prototype requires the association of domain specific heuristics into BIM objects, these heuristics are not typically available during PCD, most of the time these are known mostly by the HVAC engineer and are not commonly used by architectural designers. This research proposes the application of domain specific semantics in the form of minimum requirements, and best practices, and normative data on to BIM objects. In the context of laboratory design minimum requirements these are usually articulated regarding the space types required in the facility program, for each of these space types; design guidelines and best practices define provisions for; minimum dimensions, environmental conditions, ventilation rates, serviceability constraints, equipment performance and environmental safety. These provisions deal mostly with laboratory process spaces and in most cases, disregard building common spaces such as: elevators, storage, or toilets. In traditional PCD the HVAC engineer would include provisions for general building common spaces when performing the estimations for the HVAC system requirements. For the implementation of the LVDA then is required the development of a comprehensive data set capable of containing provisions for both process driven spaces types and building common spaces types. The classification of process driven spaces is done based on all the spaces in which scientific activities are conducted. The data values embodying code provisions and best practices are part of the LVDA input file.

In this research this data has been extracted from widely adopted domain specific codes and guidelines [4,23,24,36]. The DHAM execution structure; opens the BIM data base and creates a set of attribute containers associated to all space objects in the BIM. It labels the set "LVDA HVAC data" to allow for their retrieval and reuse in later stages of design. The module then loads the LVDA input file, this contains the default values for the provisions extracted from best practices and design guidelines, these are selection of these is based in those identified in the indoor climate simulation to HVAC design IFC model view definition, developed by Voulle in 2007, which describes the minimum data to support the process of design for climate simulation. This definition takes on the concept of BIM data views, these describe the minimum data required to comply with the requirements of specific business process. In the case of the indoor climate simulation to HVAC design, the parameters identified here are meant to support a wide range of simulation engines for the domain of HVAC. The LVDA set contains the following parameters:

- Minimum extract airflow
- Minimum supply airflow
- Design cooling power
- Design heating power
- Ventilation airflow
- Space usage schedule type

The previously mentioned data se parameters will be utilized by the LVDA prototype to calculate the building cooling loads, ventilation rates, exhaust rates, etc. The DHAM was designed to support a high level of flexibility for end-users; the module can operate on a wide range of development levels and design granularity. This flexibility can be achieved by end-users by manipulating the space names in the LVDA input file to represent different types of spatial aggregation, this allows for the energy estimation on both low and high levels of design definition. At the same time the functional structure of the system can also be customized by end users by modifying the values contained in the LVDA input file. This allows for the modification of attributes when higher levels of semantic development are reached in later stages of design. The use of user-editable input files will also allow for the modification of the system; for the assessing of other types of ventilation driven facilities, such as hospitals, microelectronics assembly.

### 5.6. DHAM Operation

The DHAM algorithm goes in the BIM data base and searches for each of the attribute names contained in the LVDA input file then, proceeds to create data containers in the BIM database for each of them, it goes and queries the BIM database and retrieves each of the space objects in the building model. With each of these it looks in them for the long name of the object and tries to map it to one of the names contained in the LVDA input file. When a match is found, the algorithm goes in to the LVDA input file and retrieves the value of each of the parameters associated to it. In case one of the space names in the BIM does not map into any of the space names in the LVDA input file; a warning of incomplete input file, is sent to the end user through the BIM UI. After the warning is sent the execution of the DHAM is terminated, this is done to reduce the possibility of false feedback from the estimation process. There are two types of attributes dynamically assigned by the DHAM: direct mapping attributes, and space-based attributes. The direct mapping attributes refer to those which are independent from the actual spatial properties of the space. They require no processing from the DHAM; such is the case of minimum temperature which only depends on the space usage. The space-based attributes require of a direct association between the attribute and the spatial properties of the space, this is the case for parameters such as occupancy load, or minimum ventilation. Space based attributes in most cases deal with space instance level information and require for the retrieval of spatial properties for their computation. For instance, in the case of the minimum ventilation rate it would be necessary to retrieve the air exchange rate per room type from the LVDA input file and the space instance volume from the BIM to be able to compute the minimum ventilation in cubic feet per minute. During the execution of the DHAM mapping process, if a space-based attribute needs to be computed; the module extracts the re-quired spatial information to compute the appropriate value before assigning the computed parameter to the space attributes.

## 5.7. DHAM Operational Structure

Development of the Air distribution Routing Estimator Module (ADREM) The second phase of ventilation engineering estimation produced by the LVDA is the routing and performance of the air distribution system; this is not commonly available in traditional engineering of ventilation systems in PCD. In this research this phase represents a mechanism for integrating the estimation of building systems performance to the properties of the architectural layout. During this phase the LVDA derives the following from the BIM, building morphology, airflow pressure structure, spatial adjacencies. These provide the LVDA with the information required for the estimation of the properties and performance of the air distribution systems that would better suit the PCD layout. Morphology derivation Module (MDM) The first step during the execution of the ADREM is the derivation of the building layout morphological features; this has a direct impact on the order in which the ADREM algorithms are executed. The MDM analyzes the PCD BIM looking for spatial properties which indicate the design being either an interstitial or a service shaft type of facility, please see Figure 9. The building level morphology derivation informs the LVDA prototype about the behavioral constraints to be applied for the ventilation system engineering estimation. We deal with the derivation of laboratory building morphology with the application of three different approaches; firstly, the verification of the existence of interstitial spaces in the BIM, this is done by querying the BIM for spaces which long name is interstitial space, this is understood by the system as a dedicated space capable of servicing process driven spaces located directly above or below it. Secondly searching for the spatial proper- ties indicating the presence of process driven spaces with floor-to-floor height capable of hosting interstitial spaces, and thirdly for those layouts in which none of the previous indicators can be identified, this is understood as a layout which belongs to a service shaft or service corridor type of building typology.

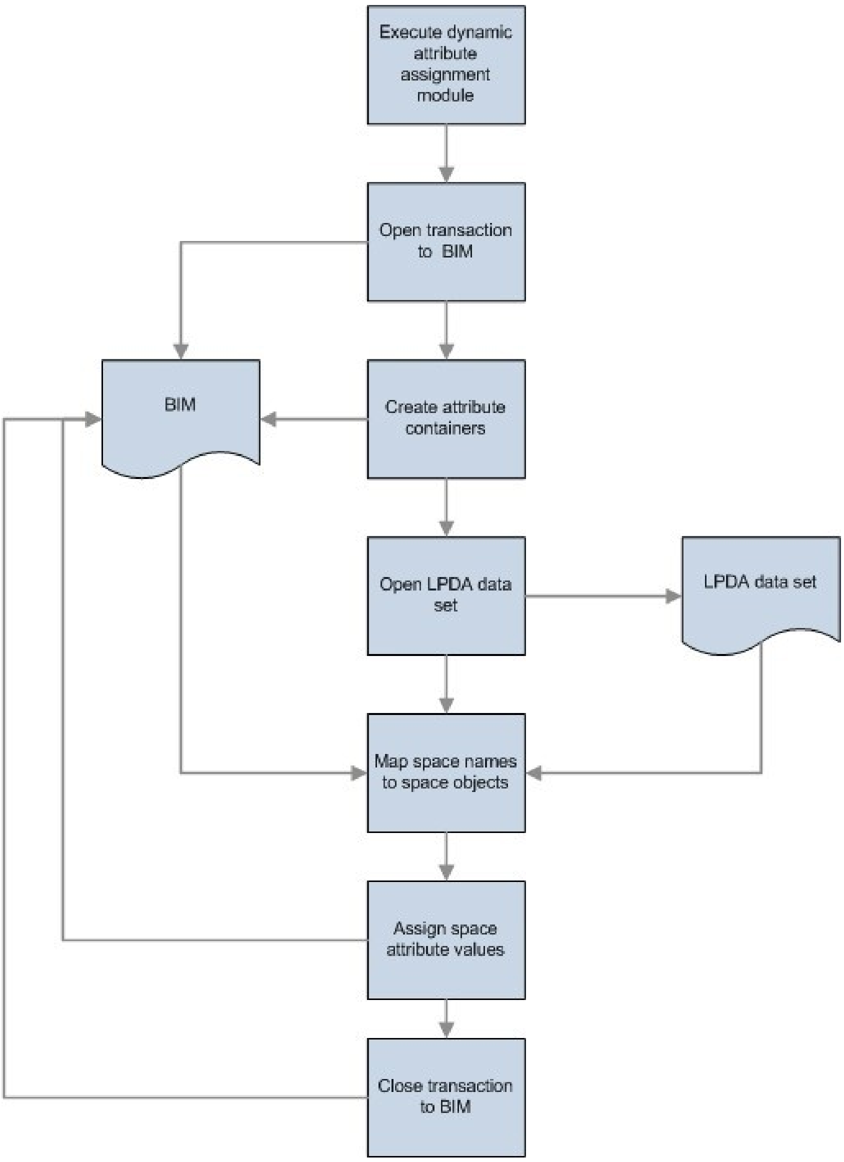



**Figure 8**. DHAM Flow chart

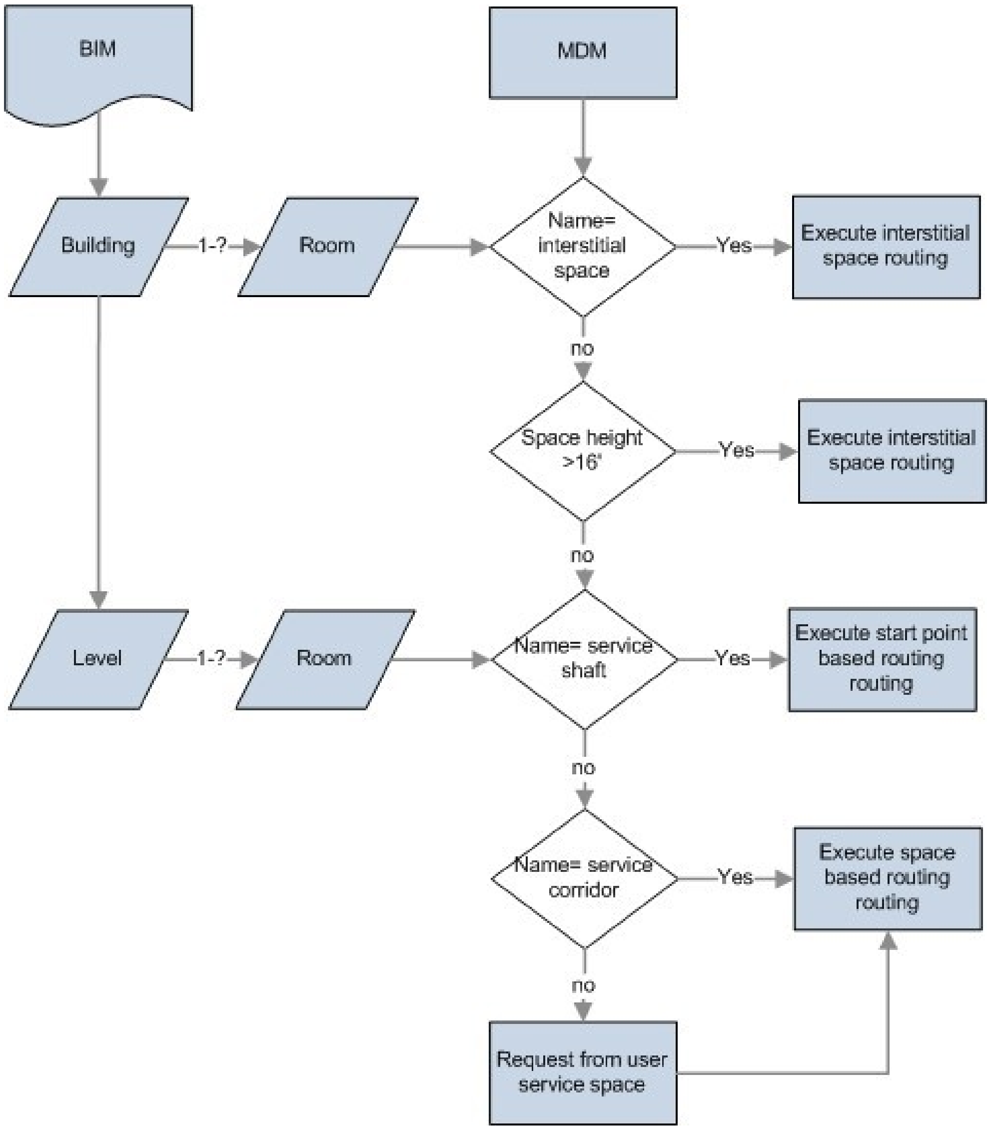



**Figure 9.** MDM Flow chart

### 5.7.1. Interstitial Space Routing

The existence of interstitial space objects in the BIM is interpreted by the LVDA prototype as the intent of having reconfigurable service systems for the laboratory. It also defines a specific relationship between service spaces and conditioned spaces; in this case the building system connectivity is constructed in the vertical plane, the vertical adjacency between service and serviced spaces is by the LVDA system to estimate the routing of the ventilation system. We propose here that such relationships can be extracted from the vertical adjacency which lies implicit in the BIM data structure. The vertical adjacency is derived by analyzing the vertical overlapping between service space and the serviced spaces. The LVDA prototype identifies the relationship of the conditioned spaces above or below the interstitial space and computes the distribution system vertical drops in accordance with the best practices guides. Deriving the vertical adjacencies in laboratory layouts Interstitial typologies require form the LVDA prototype to analyze the vertical properties of the laboratory design, during this process the LVDA retrieves the boundary geometry in the serviced spaces and evaluates their relation to the boundaries of the interstitial space. In this structure is important to note, that besides the explicit flexibility provided by interstitial typologies, the operational constraints and best practices for laboratories remain. Therefore, practices such as placing the insertion point for the HVAC close to the space occupant’s entry/exit point still is considered a good practice. Given this provision, vertical connections to service spaces should have a very specific location. Unlike later design phases, where doors can be utilized to point to the entry/exit of the space, in PCD the location of the entry point of each space is derived by the system, and explicitly associated to the interstitial space. This is then used as target point for each of the branches of the distribution system within the interstitial space itself, please see Figure 10. Then entry point is estimated by setting it at the midpoint of the common boundary between the serviced space and the circulation space, assuming the door object is not available during PCD, but this will be placed somewhere along this common bound. This approach still needs for the definition of a start space for the branch, such as a location of the fan, therefore in this model end users are required to provide the location of the fan.

### 5.7.2. Space Based System Routing

After the decision tree has traversed through the steps dealing with different types of interstitial spaces in the BIM, the MDM verifies the existence of service corridors; this is interpreted by the LVDA prototype as the design intention of having the ventilation system running through them. The MDM identifies then all the spaces which could be serviced by routing the ventilation system through the service corridor, and proceeds to estimate the adequate path. The routing functions used here are based in the explicit definition of a vertical drop adjacent to a service corridor space.

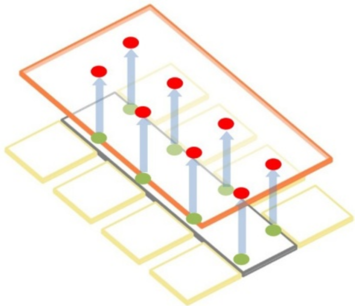


**Figure 10.** Derivation of intake points in interstitial typologies

### 5.7.3. Start Space-based Routing

The start space-based routing is built on the idea of tagging the space requiring the most ventilation in the entire layout. This is done automatically by the LVDA, the system considers this space, as suitable for the location of the system's vertical drop and this approach is taken whenever the layout does not contain definition for shafts and vertical drop spaces. When the layout contains service shafts and no service corridors; then the LVDA routing algorithm uses the vertical shafts as vertical drops for the ventilation system ducts, and the system assumes that the designer's intention is to host the ventilation branch within the circulation area. The derivation of the morphology of each ventilation branch is responsibility of the routing algorithm, particularly to the Spatial Adjacency Analysis Module (SAAM). Spatial Adjacency Analyzer Module (SAAM) An important functionality developed for the LVDA is the analysis of spatial adjacencies, since this allows it to route the ventilation system to supply spaces even if ante rooms are part of the layout, such as lobbies or sound locks or layouts including laboratory spaces with extreme requirements due to their of Biosafety level classification (BSL), such as BSL-3 and BSL-4. The SAAM allows the LVDA to build space sets including the potential target spaces, the SAAM analyzes each of the branches of the graph looking for the following scenarios: Target spaces for the ventilation system not directly adjacent to the service space but, that can be reached by the system by going through a non-process driven space such as custodial closet or lobby. Non-serviced spaces directly adjacent to the service space that might serve as anteroom for process driven spaces. Such as locker rooms. The SAAM adds to the space set list all suitable spaces directly adjacent to the service corridor, then recursively analyzes each space and all the spaces adjacent to it, this is described here as second level spatial adjacency analysis, please see Figure 11. The SAAM verifies the second level spatial adjacency and the space classification included in the LVDA prototype which indicates if the space must be supplied by the ventilation system, all spaces requiring ventilation are then added to the space set. The SAAM iterates through the space list until it runs in to; a previously visited target, a service space or a space for which there is an operational constraint for running the ventilation system through it. If the module identifies target spaces through the SAAM these and their ventilation requirements are added into the ventilation branch properties and flagged as already included in a ventilation system branch.

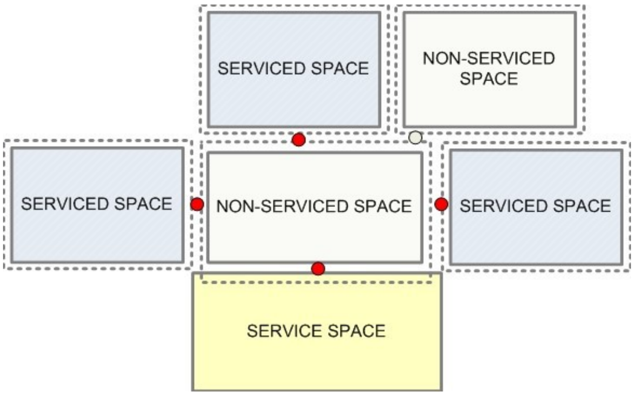



**Figure 11.** Second level spatial adjacency derivation

## 5.8. SAAM Workflow Structure

Directional Airflow Structure Analyzer (DASA) One of the extended capabilities of the LVDA analyzes the directional airflow within the layout, this functionality is based in safety guidelines, usually constructed by the engineer, it helps to identify the compliance of negative air pressure airflows towards process driven spaces. This is usually incorporated into the design documentation later during the design by the engineers (Figure 1) directional air flow mapping in cubic feet per minute: [3]. The DASA retrieves from the BIM all those spaces classified by the system as process driven spaces, the DASA then labels all of these as targets. The DASA proceeds to interrogate each target in regards of its spatial adjacencies, it checks for the directional air flow among the target and all its surrounding spaces. If during the analysis an airflow pattern which might allow for air to escape the target (process space) is detected, a warning is generated by the system. In this warning the error space the target and the building location information are identified in an error list. After all spaces in the building are analyzed the list is saved as document (.txt) and the end user is informed about the existence of errors in the BIM and the location of the error file, please see Figure 13.

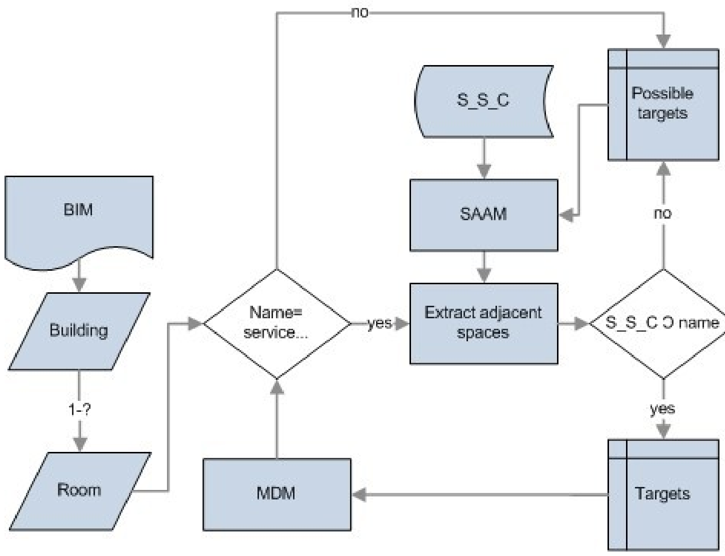
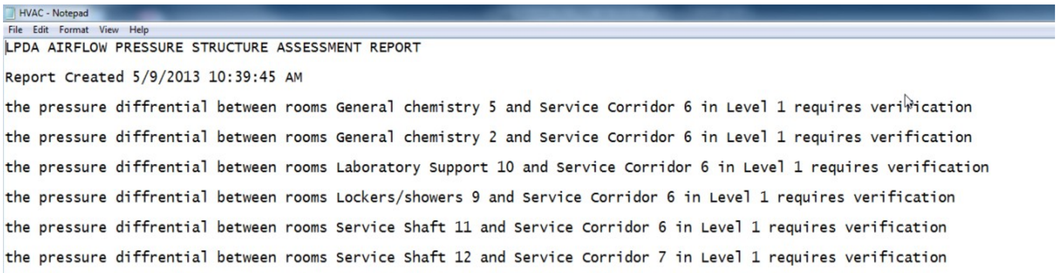



**Figure 12**. SAAM Flow chart

## 5.9. DASA Workflow Structure

### 5.9.1. Ventilation Routing Estimator Module (VREM)

Another major function carried by the LVDA prototype is the VREM, during its execution the actual building morphology is evaluated, this is done to provide an accurate estimation for the ventilation system routing, based both on layout design and ventilation system properties. At this stage the routing of air distribution ducts is derived, duct geometry, and ventilation system attributes are estimated by the LVDA prototype. The potential locations for the vertical drops are defined and informed to the end user through Revit's interface.



HVAC - Notepad
File Edit Format View Help

```
LPDA AIRFLOW PRESSURE STRUCTURE ASSESSMENT REPORT
Report Created 5/9/2013 10:39:45 AM
the pressure diffrential between rooms General chemistry 5 and Service Corridor 6 in Level 1 requires verification
the pressure diffrential between rooms General chemistry 2 and Service Corridor 6 in Level 1 requires verification
the pressure diffrential between rooms Laboratory Support 10 and Service Corridor 6 in Level 1 requires verification
the pressure diffrential between rooms Lockers/showers 9 and Service Corridor 6 in Level 1 requires verification
the pressure diffrential between rooms Service Shaft 11 and Service Corridor 6 in Level 1 requires verification
the pressure diffrential between rooms Service Shaft 12 and Service Corridor 7 in Level 1 requires verification
```

**Figure 13**. DASA text-based error report

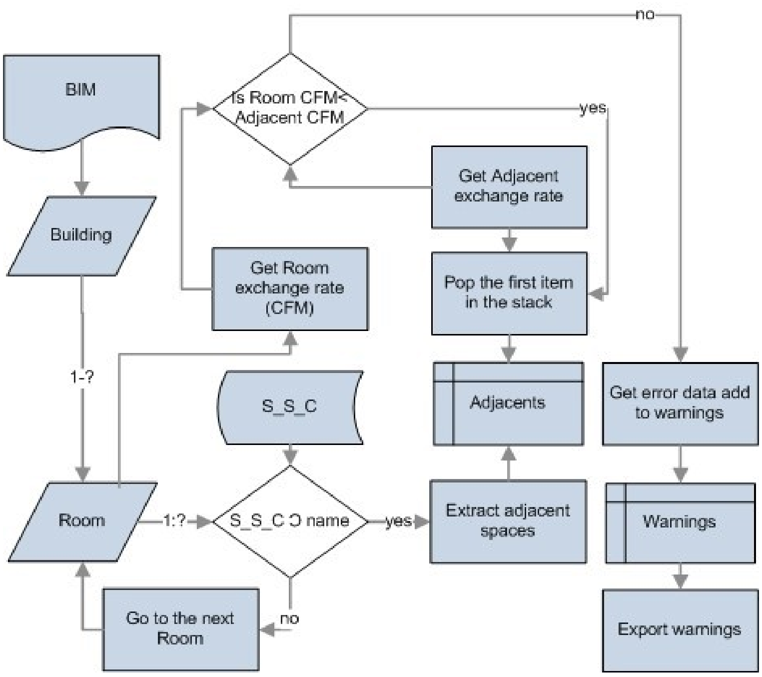



**Figure 14**. DASA Flow chart

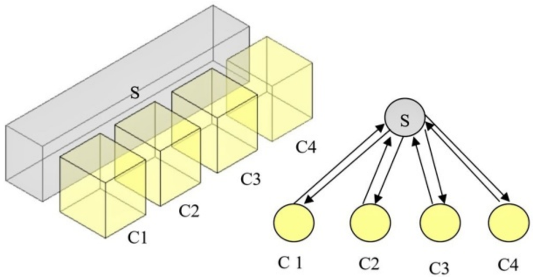



**Figure 15.** Service Adjacency Graph, representation of the spatial layout in graph form

## 5.10. Routing Estimation Derivation

Recently BIM technologies have been used to automate several aspects of building design assessment, Lee and Eastman [27] utilized neutral format BIM data for a variety of design assessments during PCD, among these the circulation and security validation. In it multiple circulation paths were analyzed regarding rules extracted from design guide- lines. Although the implementation of these has been done for a different building type and for a different type of engineering this demonstrates how building data can be used to infer the performance of circulation paths regarding design guidelines rules. In their work, Lee and Eastman [27] used graphs traversing all the possible circulation paths between what they call start and target spaces, the validation of these was done by checking the attributes of the different spaces along a potential path. An extrapolation of this approach is used in this research for the estimation of HVAC air distribution layouts. In it we identify what spaces in the model have the required conditions to host the distribution ducts and derive the apace adjacencies between this and all the serviced spaces. We propose the representation of the service-serviced spatial adjacency structure in a Service Adjacency Graph (SAG). In the SAG structure where the service space (S) acts as the root and all the conditioned spaces (C) are nodes of the graph, the construction of SAG is constrained by the adjacency relationship existing among them, please see Figure 15.

The proposed SAG structure requires the usage of the SAAM. The SAAM allows the LVDA prototype to evaluate domain specific constraints regarding the different types of ventilation systems accessibility and serviceability in laboratories. The system incorporates a space classification algorithm that allows for the construction of a well-defined graph structure. The space classification is as follows: Service spaces: these are understood as the spaces suitable for containing elements of the ventilation system running through them, these include interstitial space, service corridor, shaft, and corridor. Serviced spaces: these are all those spaces for which the LVDA input file de- fines a ventilation requirement, among these, all process driven spaces, and depending on design conditions others such as offices, and ancillary facilities. Non serviced spaces: these are all those spaces in the BIM for which the LVDA input file defines no ventilation requirements. This type of space might not require any mechanical pressurization or might even be naturally ventilated.

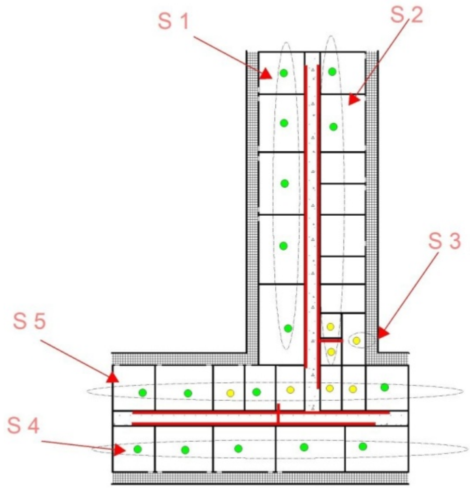



**Figure 16**. Set based representations based on the service adjacency graph

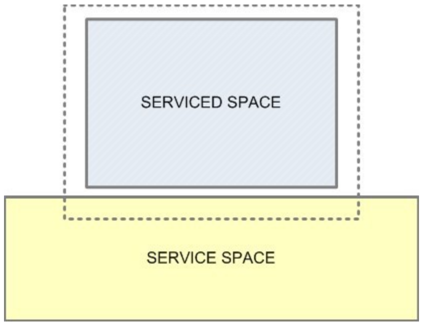



**Figure 17.** Spatial adjacency derivation through polygon offset

The SAG is used to represent the building system morphology as space sets; each of these contains all the spaces requiring service from the ventilation system, please see Figure 16. Derivation of spatial adjacency the construction of the SAG is based on the VREM capability to retrieve the geometric properties of the spatial layout indicating both; types of spatial adjacencies; direct or second level adjacency, and the estimation of the ventilation system connection points towards the serviced space. To obtain this type of information, several geometric operations and tests need to be performed. Some of these such as polygon offset, and polygon intersections, are not part of the geometric operations available through Revit's API. To enable the LVDA prototype to perform these operations it was necessary to link the LVDA to an external geometric library. This library provides the LVDA prototype access to algorithms that extend its capabilities. Many geometric libraries are available for open source use, but based on; implementation requirements, language compatibility and overall processing performance for the LVDA prototype implementation we have chosen the Clipper geometric library (http://angusj.com/delphi/clipper.php). Deriving special adjacency The derivation of spatial adjacency enables the VREM to identify the spatial relationship between the service space and potential service spaces. To derive the spatial adjacency the algorithm extracts geometric information regarding the boundaries of each serviced space, and then it translates the line-based representation coming from Autodesk Revit into a Clipper polygon object, proceeds to offset the polygon by a predetermined value, which goes further than the thickness of a standard wall object, please see Figure 17.

To determine the actual adjacency the VREM places a point at the mid- point of each of the edges of the clipper polygon, after all the points are in place the VREM uses the Clipper Point in Polygon (PIP) test to check if one of these midpoints is placed inside the service space polygon, please see Figure 18. If the test returns true, the serviced space is added to the target space set. If the test returns false, each of the edges of the will be recursively processed and tested again in a brute force approach.

The point in polygon test is based on the crossing number geometric operation, in it a ray starting in the inspected point crosses the boundary of the polygon, if the number of crossings is even then the point is outside of the polygon, of the number is odd then the point is inside the polygon, please see Figure 19. Traditional PIP algorithms perform the test by constructing a ray using the test point and extending to the right of it parallel to the X coordinate axis, then each of the edges of the polygon is tested for crossing the bounding lines of the polygon, special cases are considered when the crossing happen at a vertex or through an edge of the polygon.

Every time an adjacency is detected by the VREM, the space being tested is added to the list of spaces needing to be serviced. The properties of the ventilation branch are evaluated regarding the ventilation requirements contained in each space set which in turn determine the diameter of ducts and the required space to fit these in the service space.

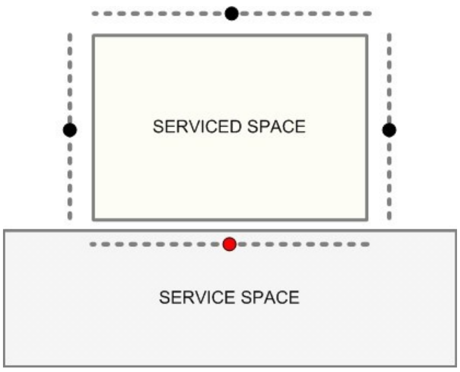



**Figure 18**. Adjacent spaces midpoint derivation

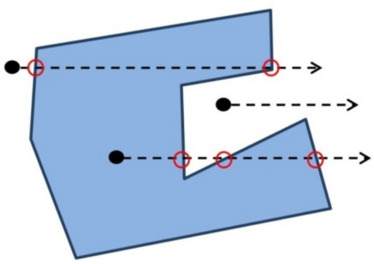


**Figure 19.** Point in polygon test diagram

## 5.11. Route Estimation Module (REM)

The points constructed by the VREM during the point in polygon test, particularly those defining adjacency, are interpreted as connecting points for the ventilation systems; therefore, they are used as targets to estimate the routing of ventilation branches. The estimation of the routing also involves the extraction of the geometric properties of the space in which the ventilation branch operates (service space) and the optimization of the route in terms of ventilation system performance.

### 5.11.1. Estimation of the Route for the Ventilation System

For the estimation of the ventilation system routing the REM takes the vertex identified as the start vertex of the system and looks for connection to the closest unvisited V vertex (target), once the closest is identified an edge is constructed by the REM, this new edged is tested for possible intersection with the boundary of the service space, if intersection exists, it means the constructed edge is out of space bounds and needs to be discarded. Then the connection is tested to the following close vertex. Each time a vertex is added a new E edge is created using the new V and the previous V, each edge is tested for path self-intersection and out of service space bounds condition, if this test return true, the algorithm traces back to previous V and tries a new connection, the process is iterated until all unvisited V are added to the path. If no target space is directly visible the algorithm tests the closest vertices of the circulation space and then check for more space target vertices, this approach allows the REM to operate in both convex and concave types of service spaces, please see Figure 20. This approach which is somewhat easy to evaluate in square shaped ser-vice spaces (Figure 19 routing of the ventilation duct on convex spaces), might appear a little bit more convoluted when dealing with more complex layouts, please see Figure 21.

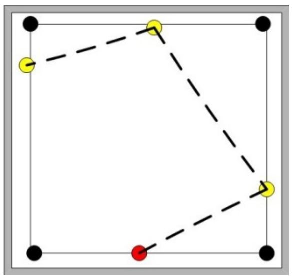


**Figure 20.** Routing of the ventilation duct on convex spaces

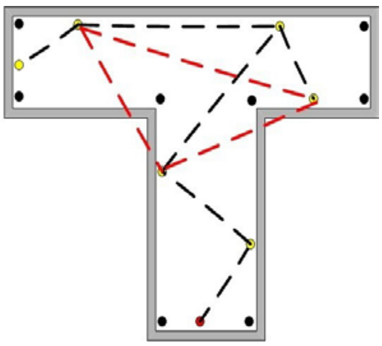


**Figure 21.** Routing of the ventilation on concave spaces

Although the developed approach at first might appear as a non-conventional solution for the routing of the ventilation duct, please see Figure 22, it is important to remember that it provides a shortest overall ventilation route and that the approach of running the ducts closer to the bounding's of the space might not the shortest path and it might produce a larger number of tee's and connections which negatively affect performance of the system.

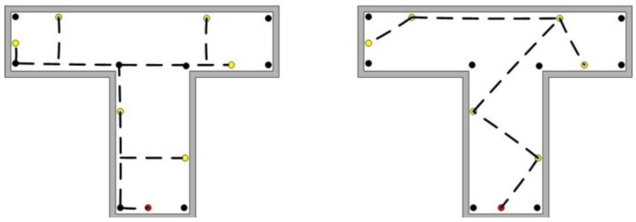


**Figure 22**. Routing of the ventilation duct, red dot indicates start point, yellow dot indicates room connection, and black dot indicates circulation room vertex

The computational implementation of the shortest path in the LVDA prototype uses a traditional computer science algorithm, developed by Robert C. Prim in 1957, Prim's algorithm solves the minimum spanning tree in computational weighted graph structure, in basic terms it searches the shortest route between all the nodes in the graph. The algorithm starts from the source S and searches among all the adjacent nodes in the graph which have not been relaxed or unvisited. Calculates the distance to them, adds to the graph the closest node V, proceeds to flag it as visited and set the V as S and continues through the graph until all nodes are visited. Unlike the original Prim's the LVDA algorithm starts from a defined node and every time a new node is added the edge created by connecting the previous and the new vertex is tested for its relation to the edges of the service space bounds, if intersection exist the algorithm falls back into the previous V and searches for another node. This algorithm deals with the metric properties of the path, meaning the length of the route and the number of connecting components, both of which influence the ventilation system performance. Estimation airflow system performance the head loss or pressure drops are understood as the decline of pressure in a ducted system, the computation of head losses can be done either manually or by using a traditional MEP software, to perform the calculation of the pressure loss is necessary to have specification for: pipe diameter, flow in the pipe, length of the pipe, viscosity of fluid, the pipe material and system components (minor losses). The LVDA prototype automates the computation of head losses by estimating the duct routing and by defaulting the other values required for the computation these. Automated calculations for pressure loss in ducts have been implemented in the past, but they still require for the design of the route and several inputs [37]. Similar to the approach developed by Jack [37], the LVDA prototype utilizes a simplified method for the calculation of losses based on the addition of both major and minor head losses: Major head loss; these are due to the friction present in ducts, pipes and pipes, in the system Minor head loss; these are due to the components of the system, such as bends, tees, valves, etc.

The total head loss of a ducted system is then calculated by the sum of both mayor and minor losses in that specific system.

$$t_{loss} = \Sigma\, t_{major\_losses} + \Sigma\, t_{minor\_losses} \tag{9}$$

Where:
$t_{loss}$ = total head loss in the pipe or duct system(Pa, N/m$^2$)
$t_{major\_losses}$ = major loss due to friction in the pipe or duct system (Pa, N/m$^2$)
$t_{minor\_losses}$ = minor loss due to the components in the system (Pa, N/m$^2$).

## 5.12. Retrieving the Mayor Head Loss of the Ventilation System

For the implementation of the LVDA prototype we defined a set of default system properties for both geometry and material composition. The LVDA prototype uses circular sections and galvanized steel for the estimation of the system performance, the material selection is a result of common practices using galvanized steel for the ventilation supply [3], and the circular section has been selected for ease of computations. In the case of the exhaust routing, it is assumed here that the exhaust configuration cannot be predefined during PCD, since there is no definition for both the composition of the gasses needing to be exhausted or the specific location of equipment inside the laboratory space, this type of information becomes available later in the laboratory design process. An important system attribute for the estimation of the head loss in the ventilation system is the duct material, this defines the roughness inside the duct which affects the motion of air through it, although in the domain of laboratory design there is a great deal of care regarding the mate- rial composition of exhausts, this is not the case for the supply system, since is assumed that just fresh air travels through it [3]. For the derivation of the distribution duct material the REM default configuration is set to be commercial steel, with a friction coefficient of 1.0 (k).

The pressure loss calculation resulting from the ventilation duct material is calculated and implemented in the LVDA prototype as follows:

$$p_{loss} = \lambda\left(\frac{1}{d_h}\right)\left(\frac{\rho * v^2}{2}\right) \tag{10}$$

Where:
$p_{loss}$ = pressure loss (Pa, N/m$^2$)
λ = friction coefficient (k)
l = length of duct or pipe (m)
$d_h$ = hydraulic diameter (m)
p = density
v = speed (m/s)

The default values are for air flow 20°C, *1.2 kg/m³* and *6 m/s*.

In general terms the hydraulic diameter is not equal to the geometric diameter of ducts (Equation 11), but for circular geometries these are equal (Equation 16) (Equation 17). There the importance of having the default geometry of the duct elements as circular, this value is applied in the pressure loss equation with no adaptation needed. The hydraulic diameter is calculated as follows:

$$d_h = 4A / p \tag{11}$$

Where:
dh = hydraulic diameter ft)
A = area section of the duct ( ft2)

p = wetted perimeter of the duct ( ft)
For circular ducts, equation 15 can be represented as:

$$\mathbf{d_h} = 4\pi r^2 / 2\pi r \qquad (12)$$

Or

$$\mathbf{d_h} = 2r \qquad (13)$$

Where:
r = pipe or duct radius (ft.)

There are three accepted approaches for the computation of the duct diameter in the ASHRAE standard 90.1: Static regain, T-method optimization, and the Equal friction method. From these the LVDA prototype uses the Equal friction method to estimate the maximum diameter of the system duct, this method can be described as follows.

Duct work equal friction method:

1. Compute the air volume in every room and branch Use the actual heat, cooling or air quality requirements for the rooms and calculate the required air volume - q.
2. Compute the total volume in the system
3. Determine the maximum acceptable airflow velocity in the main ducts Industrial systems - air velocity 8 to 12 m/s (26 to 40 ft./s) To avoid disturbing noise levels - keep maximum velocities within experienced limits: Industrial systems - air velocity 8 to 12 m/s (26 to 40 ft/s) Use the maximum velocity limits when selecting the size of the main duct.
4. Determine the static pressure drop in main duct; this should be 1.0 Pa per meter run (http://www.arca53.dsl.pipex.com)
5. Determine the duct sizes throughout the system Use the static pressure drop determined in 4) as a constant to determine the ducts sizes throughout the system. Use the air volumes calculated in 1) for the calculation. Select the duct sizes with the pressure drop for the actual ducts as close to the main duct pressure drop as possible.
6. Determine the total resistance in the system Use the static pressure from 4) to calculate the pressure drop through the longest part of the duct system. Use the equivalent length which is the actual length + additional lengths for bends, T's, inlets and outlets
7. Calculate balancing dampers Use the total resistance in 6) and the volume flow throughout the system to calculate necessary dampers and the theoretical pressure loss through the dampers.

After all the previous data has been gathered by the REM, the computation of major losses for the system can be completed. Computing the minor head loss of a ventilation system Unlike major losses, minor losses depend on the different components used in the design of the ventilation system. For the LVDA prototype we concentrate on defaulting the number of these to a limited set of components which can be commonly found in ventilation systems. The defaulting of these takes into account that for the estimation of the mayor losses, we translated all the possible configurations into circular geometries, for the estimation of the system components we follow the same approach. The minor loses for commonly found components are found in the following table (Table 2).

**Table 2. Recommended duct sizing**

| Maximum Air Volume Flow | | | | |
|---|---|---|---|---|
| | | CMH | CFH | CFM |
| | | | Industrial systems | Industrial systems |
| | | | Main ducts | Main ducts |
| Diameter | Diameter | Speed M/s | Speed ft./s | |
| (mm) | (inches) | 10 | 32.8 | 1969 |
| 63 | 2.4822 | 112 | 3953.6 | 65.89333333 |
| 80 | 3.152 | 181 | 6389.3 | 106.4883333 |
| 100 | 3.94 | 283 | 9989.9 | 166.4983333 |
| 125 | 4.925 | 442 | 15602.6 | 260.0433333 |
| 160 | 6.304 | 723 | 25521.9 | 425.365 |
| 200 | 7.88 | 1130 | 39889 | 664.8166667 |
| 250 | 9.85 | 1766 | 62339.8 | 1038.996667 |
| 315 | 12.411 | 2804 | 98981.2 | 1649.686667 |
| 400 | 15.76 | 4522 | 159626.6 | 2660.443333 |
| 500 | 19.7 | 7065 | 249394.5 | 4156.575 |
| 630 | 24.822 | 11216 | 395924.8 | 6598.746667 |
| 800 | 31.52 | 18086 | 638435.8 | 10640.59667 |
| 1000 | 39.4 | 28260 | 997578 | 16626.3 |
| 1250 | 49.25 | 44156 | 1558706.8 | 25978.44667 |

**Table 3. Minor loss coefficient for common duct components.**

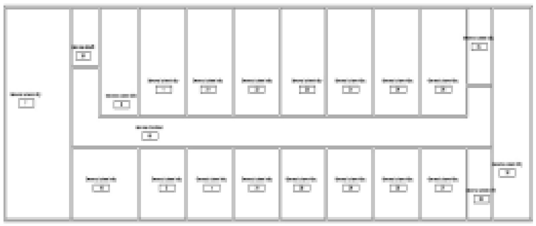
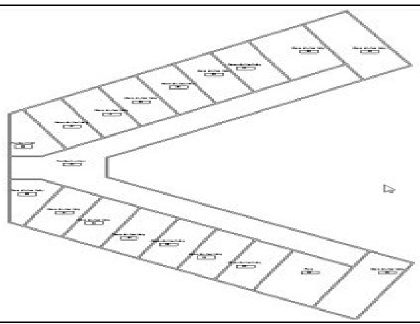
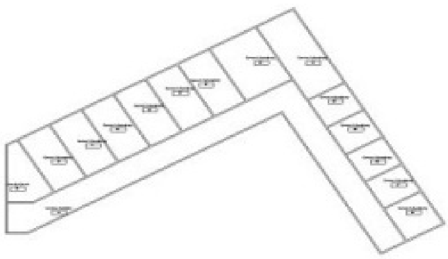
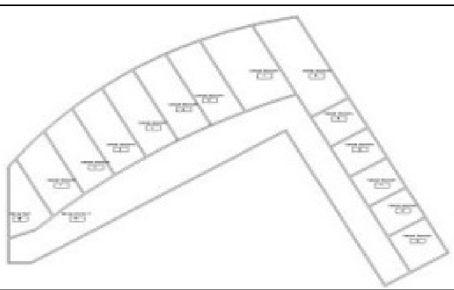
| REM Type | Component or Fitting | Minor Loss Coefficient |
|---|---|---|
| A | 90 ◦ bend, rounded radius/diameter duct ¡1 | 0.5 |
| B | 90 ◦ bend, rounded radius/diameter duct ¿1 | 0.25 |
| C | 45 ◦ bend, rounded radius/diameter duct ¡1 | 0.2 |
| D | 45 ◦ bend, rounded radius/diameter duct ¿1 | 0.05 |
| E | T, flow to branch (applied to velocity in branch) | 0.3 |

The REM maps each of the space connections to a component type E (Table 3), turns in the ventilation system path are defaulted to; A, B, C, D depending on the geometry of the turn. The LVDA translates the pressure losses of the system b/in2 into CFM reduction for the ducted system, this is done to provide designers with an output that can be easily understood by non-experts in ventilation engineering design. VREM user feedback For the LVDA prototype to provide useful ventilation engineering system feedback to users, the VREM needs to display it in ways not only easy to understand by the architectural designer but also in formats that can support the comparison between design alternatives. Once the LVDA prototype estimates the cooling loads for the BIM, the VREM computes the effective lengths of the distribution system components, number of turns per distribution branch, and numbers of space connections per branch are computed. All the numeric feedback is displayed both on the Revit UI, and also placed in a text based file(.TXT) summary report, this file contains a time stamp that allows the end user to compare the results for different layouts or options, this text file is file specific and appends each ventilation engineering estimation run completed, the VREM also constructs a graphic representation of the estimated ventilation system route, this is mapped in to the graphic interface to serve as visual reference of the system routing to end users.

## 6. Evaluation

It is proposed here to calibrate the LVDA ventilation engineering estimates by comparing them to those provided by Trane Trace 700, a well- established simulation tool for the purpose of HVAC design. Both the LVDA prototype and Trace 700 will perform the ventilation system estimation of a traditional laboratory wing model containing 20 spaces. The results will then be compared and evaluated as means of highlighting the attributes of each approach. Then, and to evaluate the ease of assessing different design options with both approaches, the BIM layout will be modified and retested. Modeling and system performance estimation, it would take about 10 to 15 minutes to an Autodesk Revit user to generate each of the different layout options defined in the study (Table 4), and less than 23 seconds to produce ventilation system engineering feedback using the LVDA. In the case of Trane Trace 700 the total time for the re-modeling proposed alternatives requires the definition of about 130 parameters, just the definition of these would take about 14 minutes, plus the time required to extract the geometric properties of each room in the design, which is incremented proportionally by the number of rooms in the model. In the case of alternative 1 (Table 4, row 1) the overall modeling time in Trane Trace 700 is about 40 minutes. Each of the ventilation systems engineering processes in the LVDA have different levels of performance due to the nature of the computational process needed to produce the feedback, a summary of the LVDA prototype performance when processing the different test models can be seen in Table 4. Notice that each iteration of assessment is indexed into a text-based output file, Therefore, and based on the programmatic constraints defined at the beginning of this section, it would take between 12 to 15 minutes to generate and evaluate the performance of completely different design alternatives, and between 4.6 6.4 minutes to evaluate the impact in the system performance of a design change.

**Table 4. LVDA prototype assessment performance**

| LVDA prototype estimation runtime | | |
|---|---|---|
| Design alternative | Modeling type-run time | Time to feedback type of feedback |
|  | model production starting from a new file:11 minutes | 22 seconds cooling loads,1.86 seconds ventilation system estimation |
|  | model production starting form a new file 14 minutes | 22 seconds cooling loads, 1.9 seconds ventilation system estimation |
|  | design alternative starting form alternative 1, 6 minutes | 18 seconds cooling loads, 1.7 seconds ventilation system estimation |
|  | design alternative starting form alternative 2, 4 minutes | 18 seconds cooling loads, 4 seconds ventilation system estimation |

# 7. Summary

This research has evaluated the possibilities of integrating ventilation system engineering to BIM enabled laboratory PCD, particularly in areas where close to real time feedback can assist designers to assess the impact of design changes or to select between multiple design alternatives. We have developed technologies for better integrating this type of data to design environments, so they become an integral part of the design workflows. There are intrinsic limitations to this research given by the nature of BIM CAD models for laboratory PCD, regardless this study developed approaches to improve the semantic quality of the BIM to enable the automation of ventilation system engineering, but other modeling issues remain that might affect the accuracy of the LVDA prototype, issues such as model completeness, space naming correctness can affect the quality of the feedback produced by systems such as the LVDA. Shortcomings of the developed approach can be identified in PCD input data, particularly when evaluating the types and analysis range of results provided by the LVDA prototype compared to those of traditional BPS, the latter covers a wider spectrum of analysis parameters which undeniably provides a more comprehensive under- standing of the expected building behavior, when compared to the LVDA. Traditional BPS might produce more accurate results but is important to evaluate the correlation between the types of evaluation and the speed of feedback produced by the different approaches, and how these fit different stages of design. Since ventilation is such an important aspect of laboratory design, postponing other types of assessment areas very early in the design process in favor of ventilation system engineering, can be advantageous for the design outcome. It is assumed in this research that in the context of PCD of laboratories a faster, close to real time, and more interactive feedback is a valid trade-off for wider range of assessment parameters and accuracy of the results. There is no real trade-off between the LVDA when compared to traditional approaches for computation of ventilation engineering in PCD.

The LVDA might even be more accurate since there is no need for human extraction of model geometry, which can easily generate assessment feedback errors. It might be argued that domain expert data mapping to the model can only be done by engineers with years of experience, but in most cases this expertise is based on vast knowledge of code requirements and best practice guidelines; all these can be documented and deployed using the developed framework. In terms of the efficiency of the system developed here, at this point and without extensive end user evaluation it is hard to produce hard metrics regarding its ease of use, but it must be noted the comparative efficiency in two specific areas, firstly, in the process execution speed (compare the two developed process models), secondly the amount of data items required by both the traditional approach and by the LVDA prototype. Also it is important to mention that; at the level of efficiency metrics even for traditional approaches, it is hard to evaluate their accuracy in predicting behavior when compared with the actual building operation, but it is important to notice that the estimation of systems proposed here is not meant to simulate the behavior of the building or the system associated to it, but to provide a rigorous approach for the estimation of ventilation system engineering to be used for design decision making, either for the purpose of design modifications evaluation or for best alternative selection. We believe that having these forecasting capabilities extremely early in the design process is a valid trade-off to traditional approaches to estimating the performance of the facility. Systems such as the LVDA are capable of better integration to PCD alternative analysis, and this approach is better than basing the PCD of laboratory design decisions in terms of rules of thumb or must reduce the speed of the design process so specialists can provide feedback. We also believe this trade-off is valid even for when designers know how to use a traditional BPS tool, so they can avoid the time-consuming task of input a vast number of parameters to get any type of feedback to proceed with laboratory PCD.

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