

**A FRAMEWORK FOR THE IMPLEMENTATION OF
AUTOMATED LABORATORIES VENTILATION SYSTEM
ENGINEERING SUPPORTED BY BIM CAD**

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Presented to
The Academic Faculty

by

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**A FRAMEWORK FOR THE IMPLEMENTATION OF
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GLOSSARY OF TERMS

ADREM: Air Distribution Routing Estimator Module

AE: Architect and Engineers

API: Application Programing Interface

ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers

BIM: Building Information Modeling

BPM: Bussines Process Model

BSL: Biosafety level

CAD: Computer Aided Design

CD: Concept Design

CFM: Cubic Feet per Minute

DASA: Directional Airflow Structure Analyzer

DD: Design Development

DHAM: Dynamic Heuristics Assignment Module

ECM: Enthalpy Calculator Module

HLCM: Heat Load Calculation Module

HVAC: Heating Ventilationg and Air Conditioning

IFC: Industry Foundation Classes

Labs21: Laboratories for the 21st century

LBNL: Lawrence Berkeley National Laboratory

LCD: Late Concept Design

LVDA: Laboratory Ventilation Design Advisor

MDM: Morphology Derivation Module

MEP: Mechanical, Electrical and Plumbing

NIH: National Institutes of Health

PCD: Preliminary Concept Design

REM: Routing Estimator Module

SAAM: Spatial Adjacency Analyzer Module

SAG: Service Adjacency Graph

UI: User interface

VREM: Ventilation Routing Estimator Module

WDCM: Weather Data Calculator Module

CHAPTER 1

Introduction

This dissertation describes research developed in the area of automation of ventilations systems engineering in laboratories, 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 (Eastman, 2011). Our research concentrates in developing computational technologies for enhancing designer's capabilities to perform design decisions or evaluations in the area of ventilation systems engineering particularly in design phases where rules of thumb have been applied until now.

We describe here new methodologies for embedding laboratory ventilation system engineering domain heuristics in contemporary Computer Aided Design (CAD) software; this is done to achieve close to real time engineering feedback, therefore, facilitating the integration between laboratory ventilation system engineering and architectural design workflows.

This research has been developed in the context of laboratory buildings, since for these the correct design and operation of Heating Ventilation and Air Conditioning (HVAC) systems is critical for the adequate operation of the facility. This 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 type of systems, the operation of ventilation systems can account

for about 50% of the energy usage of the facility (Weale, Rumsey;2001). Because of the intimate relation existing between laboratories and their ventilation systems we concentrate our research in the domain of ventilation systems engineering and it's relation to building design.

Ventilation systems engineering is intrinsically connected to the design of laboratories, different types of these are applied at almost every step of the design process from Preliminary 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 tools require complex data modeling, before any feedback can be provided to designers (Bazjanac, 2001). 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 and improve on what is considered traditional practices in the estimation of ventilations systems engineering during PCD, and how the 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

Thesis contents

The information contained here delineates the logic applied in their development and the technologies utilized for their implementation:

- Chapter 2 – Thesis hypothesis

This chapter describes the research questions that define the research efforts described in this thesis.

- Chapter 3 Methodology

This chapter describes the methodology used for the documentation, translation, and implementation of ventilations systems engineering of laboratories.

- Chapter 4 – Implementation

Computational approaches used for the development of the LVDA, described here; the procedures required for implementation of the mechanisms developed to support the LVDA assessment capabilities.

- Chapter 5 - System evaluation

Test cases are documented and tested both using the LVDA and a traditional BPS tool, a comparison is established among traditional practices and the proposed approach.

- Chapter 6 – Summary and conclusion

Here we evaluate the outcomes of this research its limitations and opportunities for further exploration.

CHAPTER 2

Thesis Hypothesis

Thesis hypothesis #1

This thesis proposes that BIM applications can support the implementation of close to real time engineering calculations for the purpose of laboratory ventilation system estimation. This is demonstrated with the development of a design assistant software prototype.

The computational assistance developed here investigates methodologies to take advantage of the semantic complexity of BIM CAD to support close to real time laboratory ventilation engineering estimation. This allows for a better integration to design workflows of ventilation engineering and the move upstream the design process this type of assessment data.

Traditional laboratory design workflows incorporate some form of ventilation engineering at almost every step of the design process, but at very early stages of the design process the use of ventilation engineering knowledge is restricted almost purely to rules of thumb applied by the architectural designer, such as 16' clearance from floor to floor to fit the ventilation ducts. The LVDA prototype operates as a domain specific computer system capable of establishing a correlation between laboratory design and ventilation engineering estimation. The system operates through the formalization of normative calculations and best practice provisions within BIM platforms.

The LVDA provides laboratory designers with forecasting capabilities commonly available only in late stages of design in the form of traditional Building Performance Simulation (BPS) tools. The technologies developed in this thesis will provide designers with the capability of analyzing different design configurations regarding the ventilation system engineering performance and to assess the impact of design changes in the performance of these systems.

Thesis hypothesis #2

We propose that, the implementation of domain specific guidelines and best practices in the form of algebraic structures applied in to BIM CAD can be used to automatically produce data models for the purpose of producing ventilation engineering feedback as to support design decisions during laboratory PCD.

Many domain specific guidelines and best practices compilations exist for the engineering of laboratories ventilation systems, in many cases these develop in to rules of thumb applied by designers when swift engineering feedback or expertise is required. The effectivity of these is based on the level of expertise and the consistency in application provided by the human applying the rule of thumb.

This research develops an approach for the automated generation of ventilation systems engineering data models, based on best practices and guidelines and the computational operations required for the efficient application of these to BIM design data. Based on these data models we develop a prototype which will provide swift and simplified ventilation engineering assessment feedback in areas

were traditional ventilation engineering PCD assessment data is required, such as the computation cooling loads .The prototype will also extend the scope of the feedback to areas which have an important role in the correct design of laboratory ventilation systems, but are usually available only in later stages of design such as FCD or DD.. The extended PCD feedback will include ventilation airflow pattern analysis, ventilation routing estimation, and geometric properties of the ventilation system.

Intellectual contributions:

- Develop software structures for the automation of ventilation system engineering forecasting of spatial requirements for the fitment of ventilation systems in laboratory facilities.
- Enhancing the process by which laboratories are designed, pushing upstream ventilation engineering assessment metrics in to PCD of laboratories.
- Automate the assessment of air flow patterns in laboratory facilities. Allowing designers to clearly identify spatial adjacency conflicts early in the design process.
- Improving the design process of ventilation intensive facilities, such as hospitals, micro electronics manufacturing. This will be done by providing a highly customizable framework for the development of ventilation system engineering estimation.

To achieve the previously stated this research has developed computational technologies supporting the implementation of ventilation engineering design assistances in the laboratories PCD, such as:

- Automating the process of embedding and mapping domain expertise in BIM data bases.
- The implementation of ventilation air flow estimation capabilities in BIM software to provide energy performance assessment capabilities.
- Derivation of ventilation system distribution routes, supporting a better analysis of the correlation between architectural layouts and ventilation system fitting
- Development of graph structure capable of representing the patterns required for the routing of building services such as ventilation, piping, conduits.

CHAPTER 3

Methodology

This research is based on an extensive literature review dealing with the design and engineering of ventilation systems for laboratories, the current state of computer software used to support the design of these and the traditional design practices and workflows for laboratory design.

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. 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; most of the computational systems for this purpose are designed to operate in late stages of design such as FCD or DD where design changes occur at a very slow pace, but where these changes might be costly. This lack of computational support 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 (LBNL-49366, 2001).

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 (McIntosh, Dorgan et al. 2001; NIH, 2003/ 2008), this becomes of extreme importance when dealing with high levels of Biosafety Level (BL) laboratory spaces (Page 66). Also laboratories require 100% fresh since their equipment exhaust cannot be recirculated, therefore more air needs to be brought in to 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 it 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, this condition must be kept at all times. In traditional practices 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 (Figure 1 directional air flow mapping in cubic feet per minute; (McIntosh, 2001)**Error! Reference source not found..**

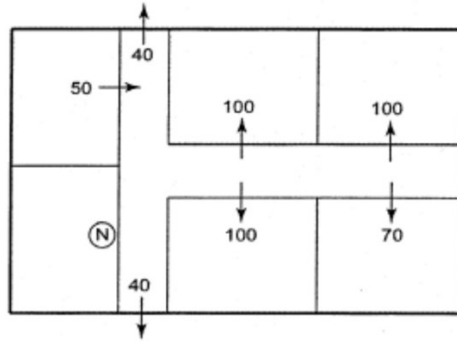


Figure 1 directional air flow mapping in cubic feet per minute; (McIntosh, 2001)

Traditional practices in the design of directional air flow networks has 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 (McIntosh, Dorgan et al. 2001; Bennett, Parks et al. 2005), 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 (Bennett, Parks et al., 2005). Bennet (2005) has pointed recently that the inward air flow can be more accurate for controlling the air flow patterns between two adjacent spaces. The design of the inward based directional airflows is directly connected to the spatial adjacency structures of the layout and the air pressurization of the different spaces in it, making this 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 of it. 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 or for the architect to perform traditional BPS, himself to test the performance of the design.

What is the 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 (BIM Forum, 2013; GSA, 2010). Among these the General Services Administration, Facilities Standards for the Public Building Service (P100) clearly establishes design 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 the P100, the semantic content for each of these is clearly defined making it a

suitable for the research developed here. In it 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 (Figure 2 preliminary concept design diagram (NIH design policies and guidelines)). 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.

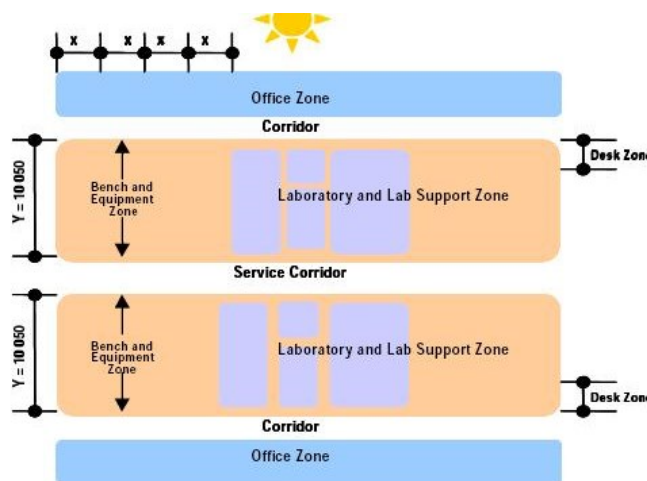


Figure 2 preliminary concept design diagram (NIH design policies and guidelines)

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 spatial 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.

Depending on the required design conditions the laboratory module can include two other program components besides the laboratory space: scientist office and lab support space. The spatial relations among these will affect both human circulation conditions and the dimensioning of the building's ventilation systems engineering. For instance, the inclusion of the scientist office within the laboratory module will negatively affect the loads on the HVAC system by increasing the area of continuously conditioned space, but the detachment of these might increase the length of pedestrian circulation.

The PCD of laboratories and engineering assessment

In the case of laboratory design, there is not a 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, 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 (Sheward, 2012).

In traditional PCD of laboratories (**Error! Reference source not found.**), after the PCD model is completed by the architect, it 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 different 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 (Diagram 1; Business Process Model of traditional PCD of laboratories (author)), is easy to infer the reasons for the inefficiency of 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.

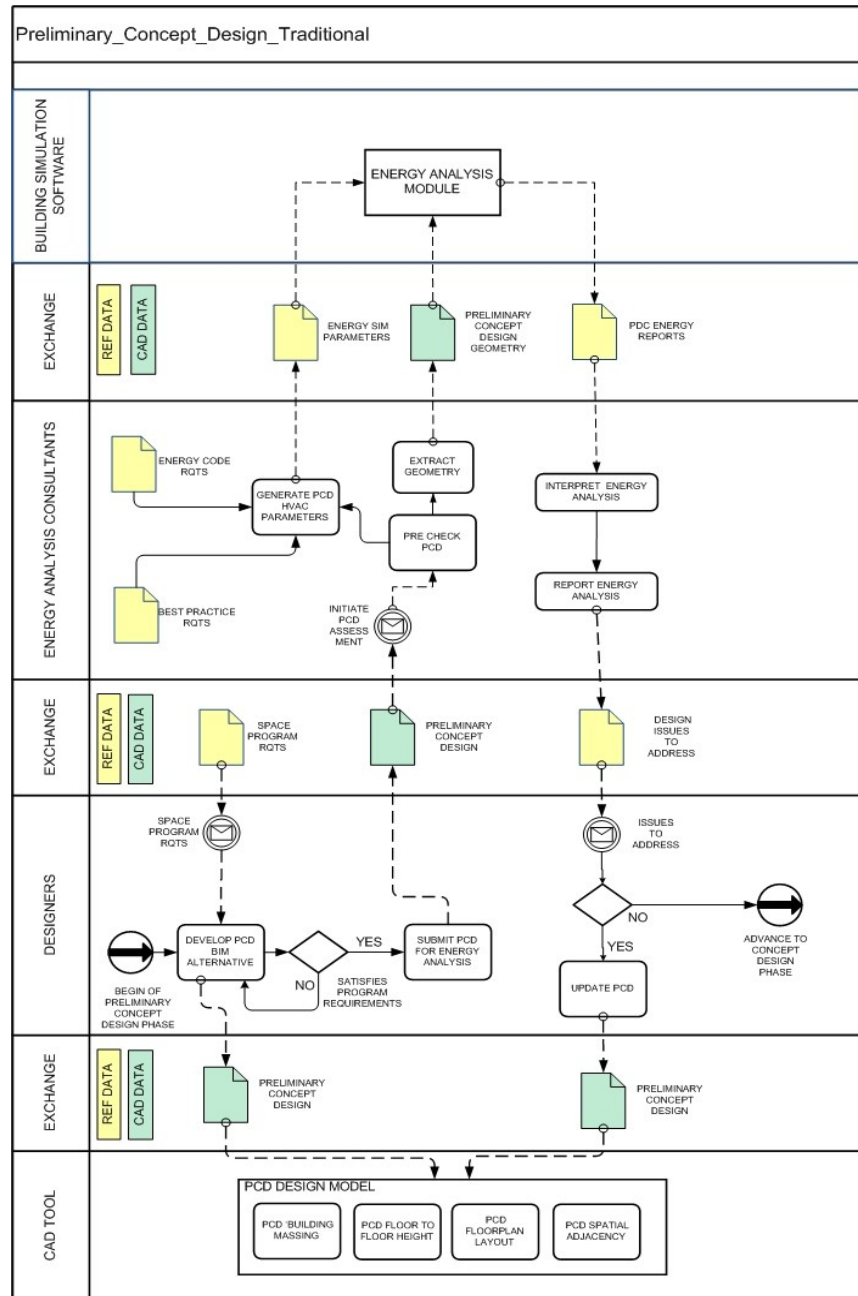


Diagram 1; Business Process Model of traditional PCD of laboratories (author)

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 the HVAC engineer will conduct a detailed analysis of the heat loads in the facility, define the ventilation rate per space, determine the airflows, and propose the duct layout including the location of vertical drops as well as other pieces of equipment. The results of the CD or FCD HVAC engineering analysis can generate a set of design revisions in order to properly fit the HVAC components and their requirements (Hegazy, 2001; Mokhtar, 1998) which due to the state of completeness of the design might produce costly revisions and time delays.

The previously described process is supported by the use of BPS by the building design team, many of these tools features makes it hard for any implementation of multidisciplinary or collaborative design environments in early stages of design (Welle, 2012). 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 as 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 (Holzer 2009) , the time required to prepare and complete BPS assessment, among others clearly limits the application of these, since once the BPS analysis has been completed the entire design might have changed making the analysis results obsolete (Bazjanac 2001) . Both Holzer (2009) and Chaszar (2006) indicate that

software's results might not enable interdisciplinary collaboration and that different domain semantics can create friction among AE design teams. Holzer (2009) also points among the issues limiting the interdisciplinary collaboration, the need for team members to reflect in privacy regarding the proposed solutions.

Current trends in engineering assistances

The development of computational BPS tools has been going on for over 40 years. The range of these varies greatly from; excel based to special purpose highly advanced software. Trčka and Hensen (2010) 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, DesignBuilder, 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, Trčka and Hensen (2010).

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 (Rousseau P.G., 1993) .

Current efforts in BPS development concentrate on improving the integration of these to the overall building design process (Augenbroe, 2001). Three main areas are being researched: the simplification of either the calculations being performed (Park, 2002), the simplification of the simulation data model being used (Kannamma, 2014), and the automating generation of simulation models for the execution of BPS (Bazjanac, 2011; Sanguinetti, 2012). This research takes on these trends and goes a step further in the effort of integration to design process by embedding engineering estimation within CAD software.

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 (ASHRAE Handbook-Fundamentals, 2013), design requirements (NIH, 2008), design guidelines (Chosewood, 2007; NIH, 2003; Dahan, 2000; DiBerardinis L et al, 2012; McIntosh, 2001), and HVAC engineering (Bell, 2000; Tedesco, 2004). 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
- 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 data: this refers to algebraic computations required for the engineering of ventilation systems in laboratories e.g. “cooling loads calculation” (equations 1 to 6).

$$\Delta h = h_{in} - h_{out}$$

Equation 1

Where:

h_{in} = enthalpy in (Btu/Lb)

h_{out} = enthalpy out (Btu/Lb)

$$\Delta T_{airside} = LAT - EAT$$

Equation 2

Where:

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

$$\text{Total Air flow} = \text{Load} * 3.41 * \frac{\text{Area}}{(1.09 * \text{Delta } T \text{ Airside})} \quad \text{Equation 3}$$

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

$$\text{Total OA loads} = \text{Total Air Flow} * 4.5 \quad \text{Equation 5}$$

$$\text{Total tons} = \frac{\text{Total OA Load}}{1200} \quad \text{Equation 6}$$

Note: The previous formulas are of common use in HVAC cooling load calculation (Bell, 2000) , Engineer toolbox web site (engineeringtoolbox).

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” (NIH, 2003).

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 (**Error! Reference source not found.**)

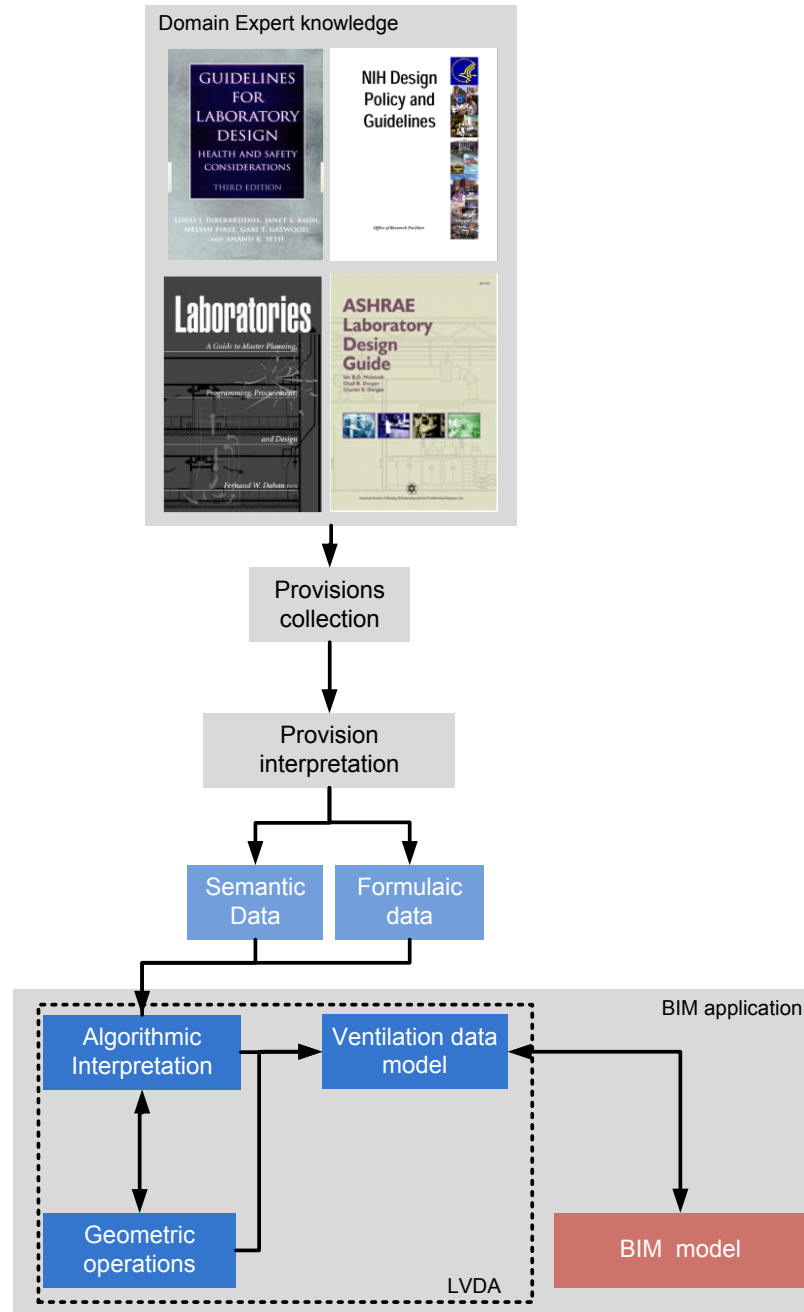


Diagram 2: methodology implementation workflows

Capturing formulaic and domain expert data

The forms for capturing knowledge vary depending on the area of expertise being processed. For instance, in some areas of architecture it might be the size of service areas in a building regarding the usable square footage of the layout, in engineering it might be the types of connectivity that a pre-cast concrete beam needs to have when installed under particular 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 (Kimura et al., 2003).

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 impact both the safety conditions of the building and the efficiency of the systems.

Capturing formulaic data: collected in the form of algebras related to either the application of semantic based knowledge and parameter processing for assessment engineering data computation , two types of formulaic data have been Identified , space based formulas, environmental conditions formulas . The list of formulas implemented in this research can be found in (**Error! Bookmark not defined.**).

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. The space instance classification has been collected in a human readable input file to support customization. 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 areas
- Service Shaft
- Interstitial Space
- Stairs

Each of these is explicitly space types is associated to a set of space attributes; these along with their values have been compiled from domain specific guidelines (Chosewood, 2007; NIH Facilities, 2008; NIH Health, 2003; McIntosh, 2001; Dahan, 2000; DiBerardinis L et al, 2012). When processed by the system these attributes are embedded by the LVDA in the BIM database, enhancing the semantics of the BIM model to both; support 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 Lehtinen (2007).

Documenting and interpreting provisions behavior

In this research we have documented provisions behavior directly in to the algorithms composing the LVDA prototype, it is understood here that the capability of 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” (NIH, 2003). 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) (Page 54).

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 instead of traditional BPS.

Lee and Eastman (2010) demonstrated how semantically rich 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.

Park and Augenbroe (2002; 2004) 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 (2004)) 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 (Harris and Conde, 1959; McQuiston, Parker et al. 1994; McIntosh, Dorgan et al. 2001, Sauer, Howell et al. 2005) to be used for the estimation of engineering ventilation systems.

CHAPTER 4

Implementation of the LVDA

This chapter describes the implementation of the LVDA, a domain specific system developed for assisting designers in the development of laboratories regarding the engineering of ventilation systems. We provide here a description of the approaches developed and implemented in the LVDA software prototype.

During the early stages of this research it was identified the need for the LVDA 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 laboratory PCD workflows. Based on these principles the system has been organized in two stage functionality that controls 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 of the modules of the LVDA have been embedded in the back end of CAD BIM software in the form of plug-in software.

Most contemporary BIM software's can extend their operational capabilities, through what is called 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 both the default capabilities of the BIM and the data base of it. Different BIM applications support the use of a variety of programming languages in their API's. The detail of the programming languages supported by BIM software's currently available in the USA is as follows:

Table 1; Architecture Design BIM software, API language interface

Software	Supported programming language
Autodesk Revit	VB.NET, C#, C++.
Graphisoft Archicad	C, C++.
Bentley Microstation	VBA, C#, VB.NET
Nemetscheck Vectorworks	C++
Gehry technologies Digital Project	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 (Khemlan 2007) uses it, and also because it's API supports the use of several programming languages, among the available we have chosen C#.

Although the LVDA prototype implementation has been done using C#, and using Autodesk Revit specific functions, high level pseudo-algorithm are also provided here to support the application and reuse of the knowledge developed here in to different programming languages and other BIM platforms.

The user interface designed for the LVDA (Figure 3; LVDA user interface 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 be dynamically loaded in to the system users might be required to take action such as to point the location an input file or connect the computer to the World Wide Web.

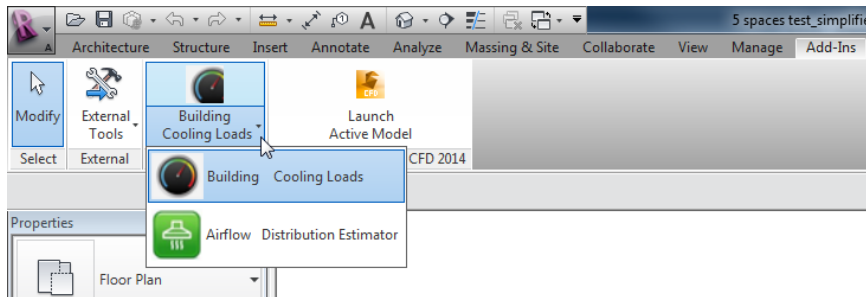


Figure 3; LVDA user interface

Development of the Heat load calculator Module

The Heat Load Calculation Module (HLCM) is 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 (Diagram 1; Business Process Model of traditional PCD of laboratories (author)).

Heat load calculation Module (HLCM)

Given the nature of the LVDA prototype, all of the operations defined for the ventilation system estimation are based on traditional engineering feedback for PCD, in this context the HLCM is in charge of 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.

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.

The runtime workflow of the HLCM has been constructed using the following approach:

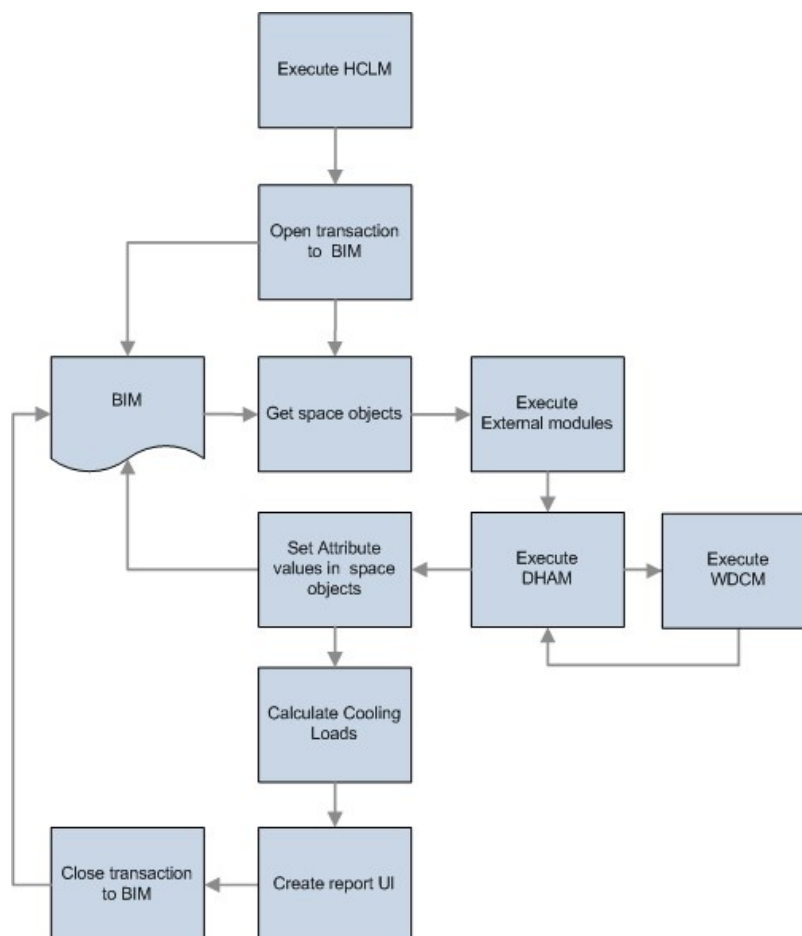


Figure 4; HLCM Flow chart

As described above 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 session. The absence of the group indicates the need for these 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, 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 screenshot shows a software interface with a table titled 'LPDA LOADS CALCULATIONS'. The table has three columns: 'Level', 'Name', and 'COOLING LOADS (tons)'. The table contains 18 rows of data. The left sidebar shows the 'Properties' panel with various settings for the selected schedule.

Level	Name	COOLING LOADS (tons)
Level 1	General chemistry	1.175462
Level 1	General chemistry	1.175462
Level 1	Teaching	1.175462
Level 1	Radio chemistry	1.175462
Level 1	General chemistry	0.125742
Level 1	General chemistry	0.147297
Level 1	General chemistry	0.13652
Level 1	General chemistry	0.114964
Level 1	Radio chemistry	0.201187
Level 1	Teaching	0.195798
Level 1	Radio chemistry	0.147297
Level 1	Radio chemistry	0.104186
Level 1	Teaching	0.179631
Level 1	Radio chemistry	0.147297
Level 1	Radio chemistry	0.114964
Level 1	Radio chemistry	0.125742
Level 1	General chemistry	0.152686
		6.595159

Figure 5: LVDA Cooling Load feedback

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.

High level algorithm and 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#, it is assumed that the provided pseudo algorithms (on page 107) and their logic can easily be reproduced in to other programming languages.

In different design phases and particularly in PCD it is hard to assume the BIM will have a certain level of completion when evaluated by computational systems (Sanguinetti, Abdelmohsen et al., 2012) 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 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 high levels of detail containing all the required space types. The only data fields which are constrained in the HLCM mapping structure are the parameter names and the types associated each space usage instance; this is done as a mechanism to keep control over the computations implemented.

Development of the Weather Data Calculator 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 information 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 (Figure 6). After the string for the location has been provided the WDCM will place it in the doc.ProjectInformation.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 through 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 (Degelman, 1997; Westphal and Lamberts, 2004) The operational structure of the WDCM is described in figure 7.

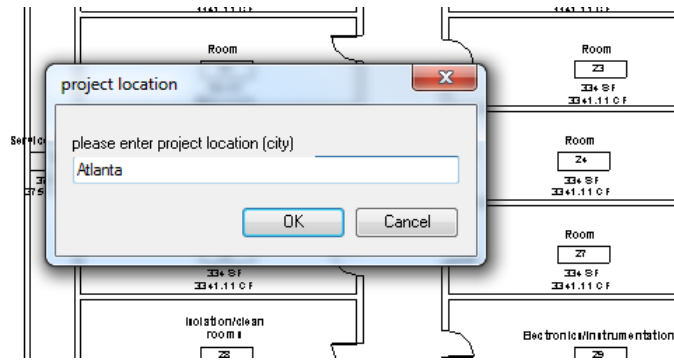


Figure 6, WDCM user interface, project location window.

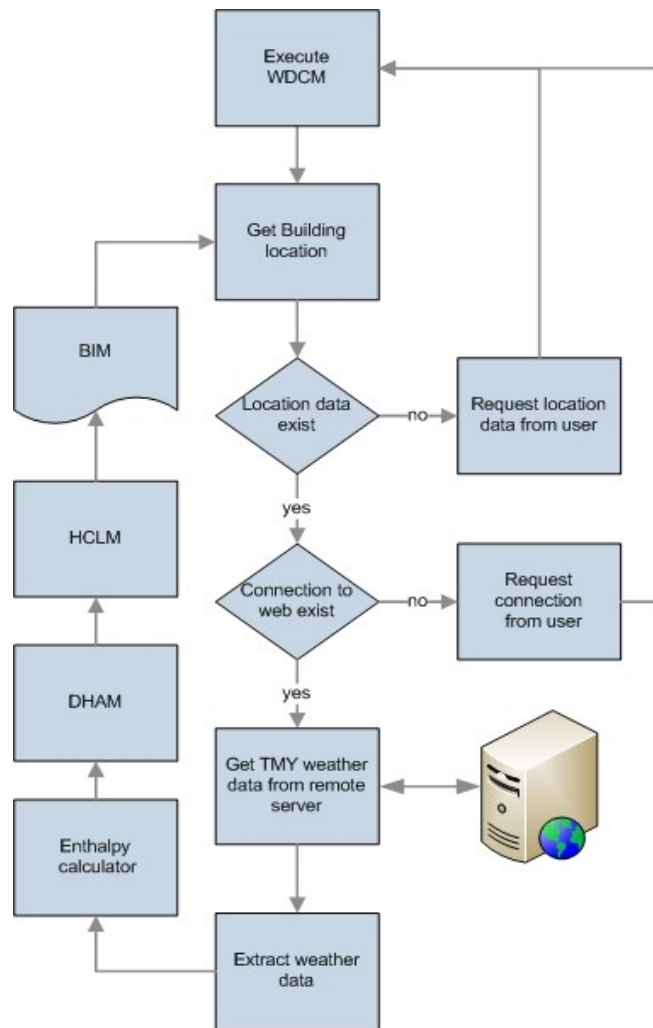


Figure 7; WDCM Flow chart

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#, it is assumed that the pseudo algorithm provided here can support the reproduction of the prototype in to other programing languages (on page 108).

Enthalpy Calculator Module (ECM)

One critical piece of data required by the WDCM to calculate the cooling load of each space object is value of enthalpy. Enthalpy is understood 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. 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, the implementation of enthalpy using C# is shown on page 110 (APPENDIX B:)

ECM General level algorithm

The implementation of the ECM is based on the application of mathematical formulas 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:

$$h = h_a + x h_w \quad \text{Equation 7}$$

Where:

h = specific enthalpy of moist air (Btu/lb)

h_a = specific enthalpy of dry air (Btu/lb)

x = humidity ratio (lb/lb)

h_w = specific enthalpy of water vapor (Btu/lb)

The calculation of humidity ratio can be expressed as:

$$x = \frac{0.62198 p_w}{(p_a - p_w)} \quad \text{Equation 8}$$

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 requirements as defined in the LVDA input file.

Implementation structure of the ECM

The computation of enthalpy is performed 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;

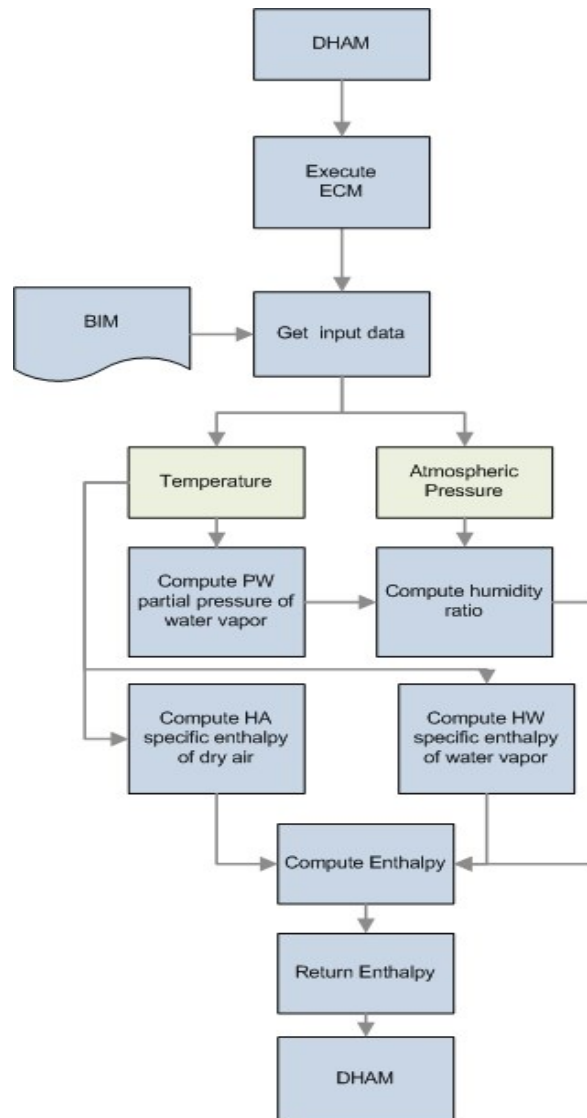


Figure 8 ECM Flow chart.

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 modules in the LVDA prototype to perform their computations. It operates by associating HVAC engineering domain heuristics to the object 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 in to 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. In the context of laboratory design minimum requirements 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 space 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 (NIH, 2008; ASHRAE Handbook-Fundamentals, 2013; DiBerardinis L et al, 2013; Dahan, 2000).

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, the selection of these is based in those identified in the indoor climate simulation to HVAC design IFC view definition, developed by Voulle (2007). 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 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 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 is capable of operating 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 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.

Dynamic Heuristics Assignment Module operation (DHAM)

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 in to 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 need to be computed; the module extracts the required spatial information to compute the appropriate value before assigning the computed parameter to the space attributes.

Module operational structure

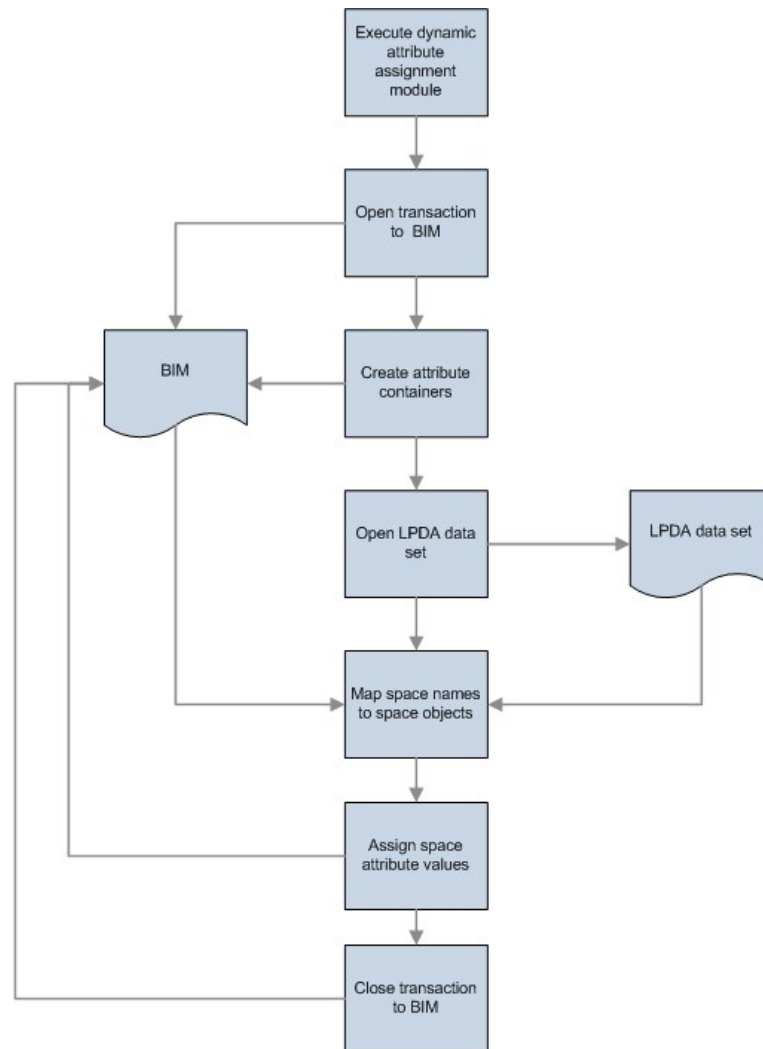


Figure 9; DHAM Flow chart

The DHAM pseudo algorithm can be found on page 107 (APPENDIX B:)

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.

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 properties 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.

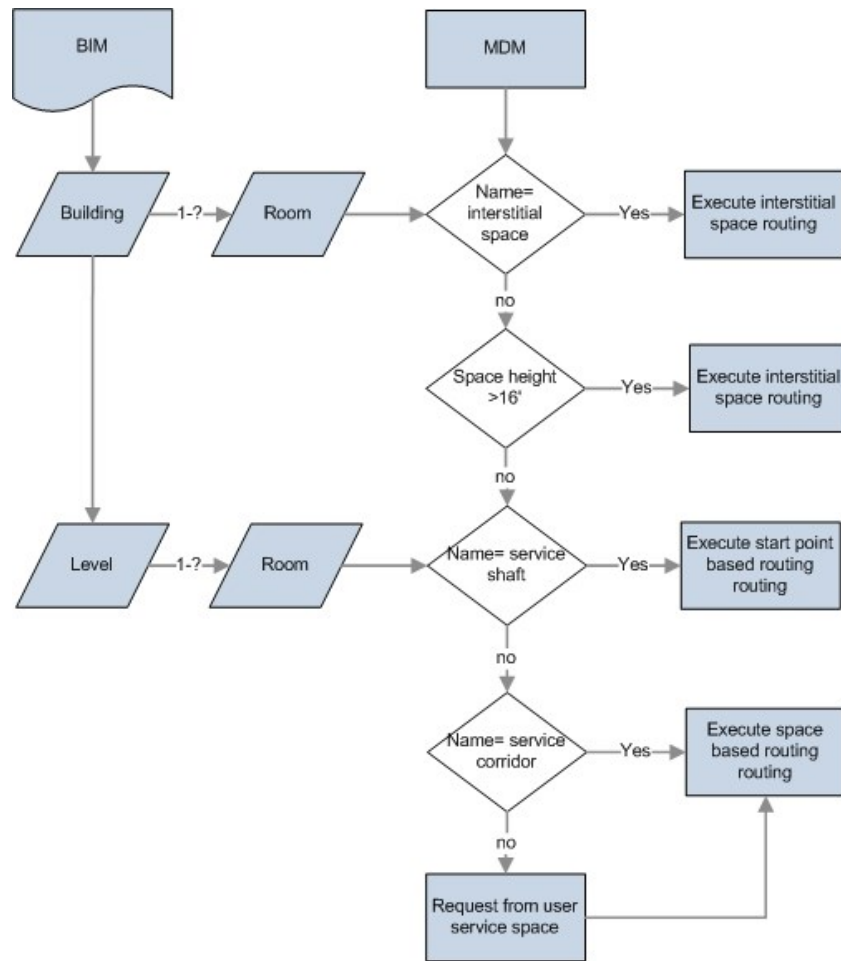


Figure 10; MDM Flow chart

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 in order 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 to the best practices guides.

Deriving the vertical adjacencies in laboratory layouts

Interstitial typologies require from 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 (Figure 11 derivation of intake points in interstitial typologies) within the interstitial space itself. 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.

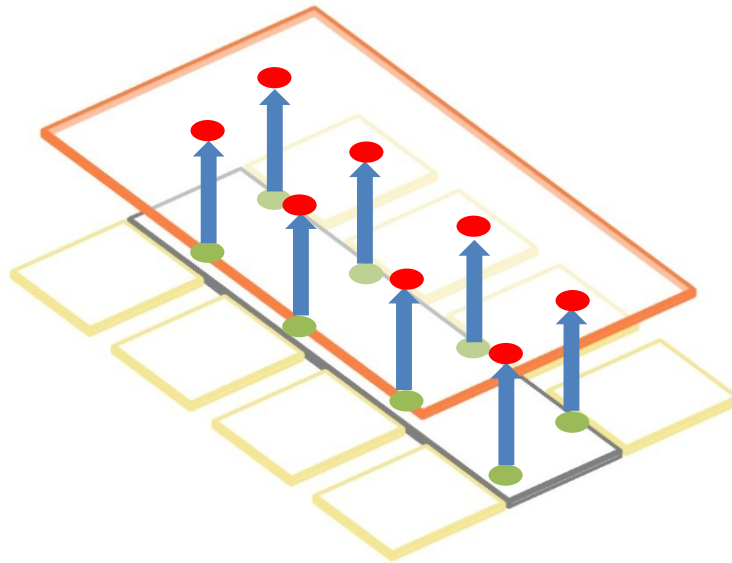


Figure 11 derivation of intake points in interstitial typologies

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.

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 (Figure 12 second level spatial adjacency derivation). 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 in to the ventilation branch properties and flagged as already included in a ventilation system branch.

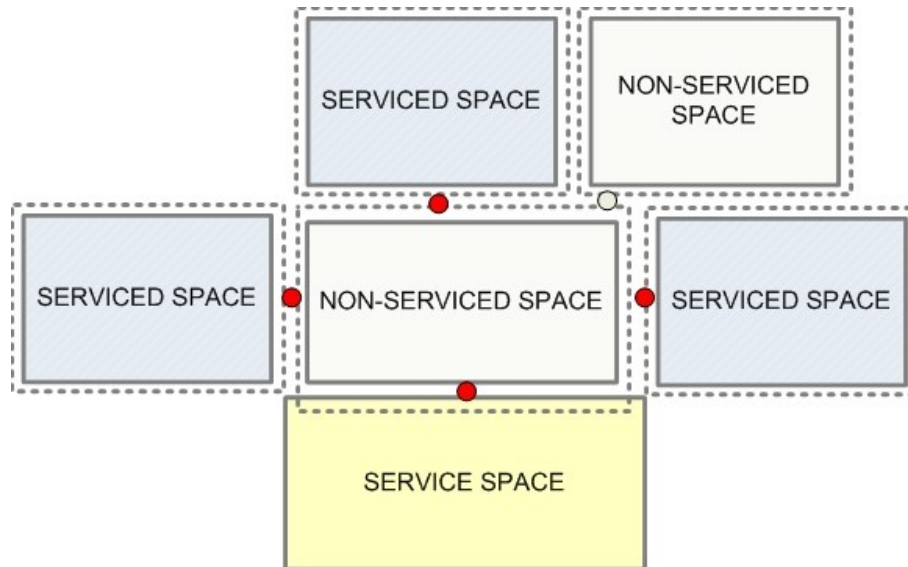


Figure 12 second level spatial adjacency derivation

SAAM Implementation structure

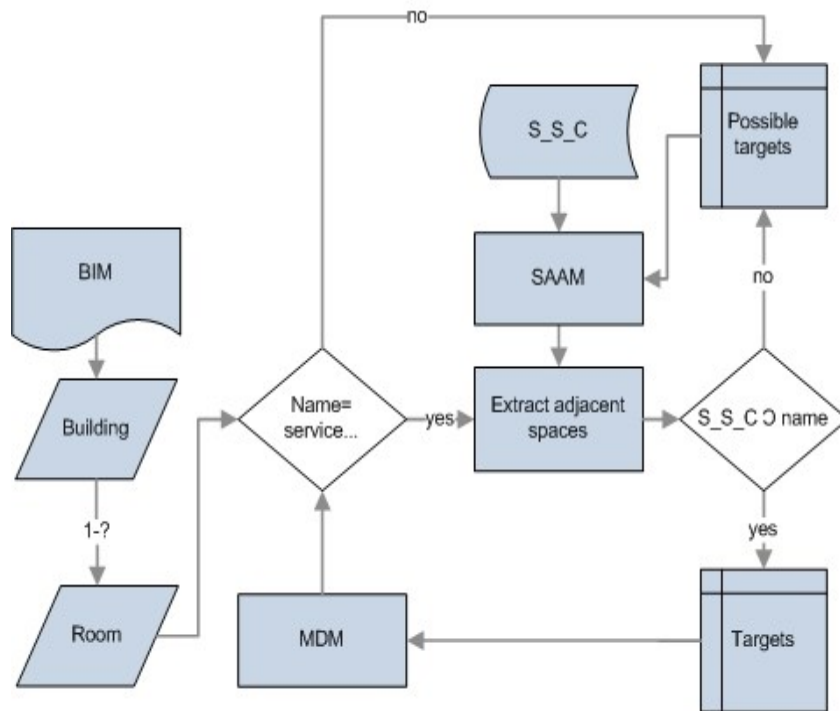


Figure 13 SAAM Flow chart

The SAAM pseudo algorithm can be found on page 107 (APPENDIX B:)

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 in to the design documentation later during the design by the engineers (Figure 1 directional air flow mapping in cubic feet per minute; (McIntosh, 2001).

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) (Figure 14 DASA text based error report) and the end user is informed about the existence of errors in the BIM and the location of the error file.

HVAC - Notepad
File Edit Format View Help
LPDA AIRFLOW PRESSURE STRUCTURE ASSESSMENT REPORT
Report Created 5/9/2013 10:39:45 AM
the pressure differential between rooms General chemistry 5 and Service Corridor 6 in Level 1 requires verification
the pressure differential between rooms General chemistry 2 and Service Corridor 6 in Level 1 requires verification
the pressure differential between rooms Laboratory Support 10 and Service Corridor 6 in Level 1 requires verification
the pressure differential between rooms Lockers/showers 9 and Service Corridor 6 in Level 1 requires verification
the pressure differential between rooms Service Shaft 11 and Service Corridor 6 in Level 1 requires verification
the pressure differential between rooms Service Shaft 12 and Service Corridor 7 in Level 1 requires verification

Figure 14 DASA text based error report

DASA Implementation structure

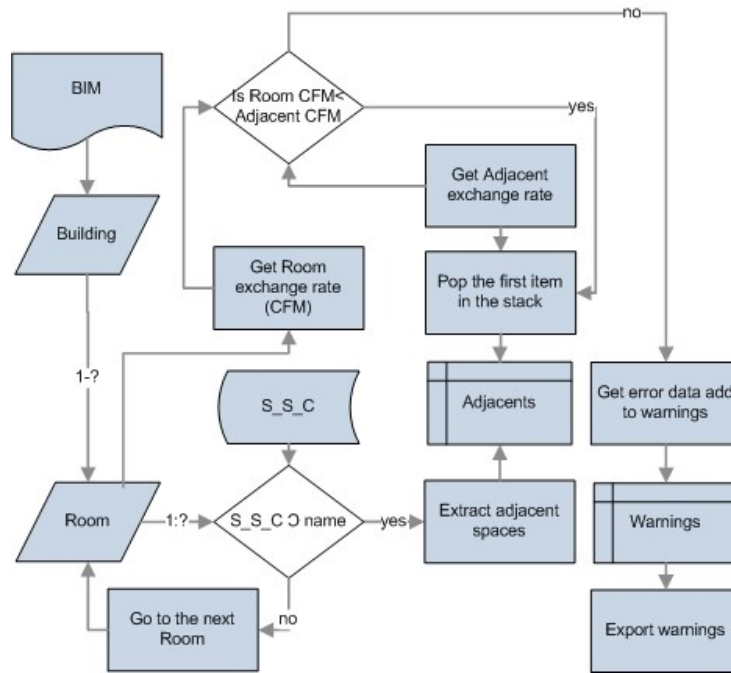


Figure 15 DASA Flow chart

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.

Routing estimation derivation

Recently BIM technologies have been used to automate several aspects of building design assessment, Lee and Eastman (2010) 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 guidelines. 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 (2010) 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 space 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 (

Figure 16; Service Adjacency Graph, representation of the spatial layout).

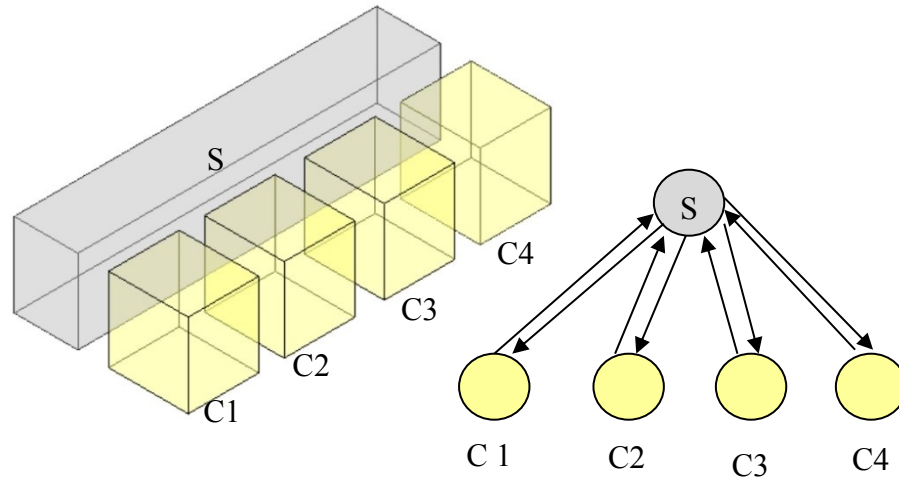


Figure 16; Service Adjacency Graph, representation of the spatial layout in graph form

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 defines 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

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 (Figure 17; set based representations based on the service adjacency graph).

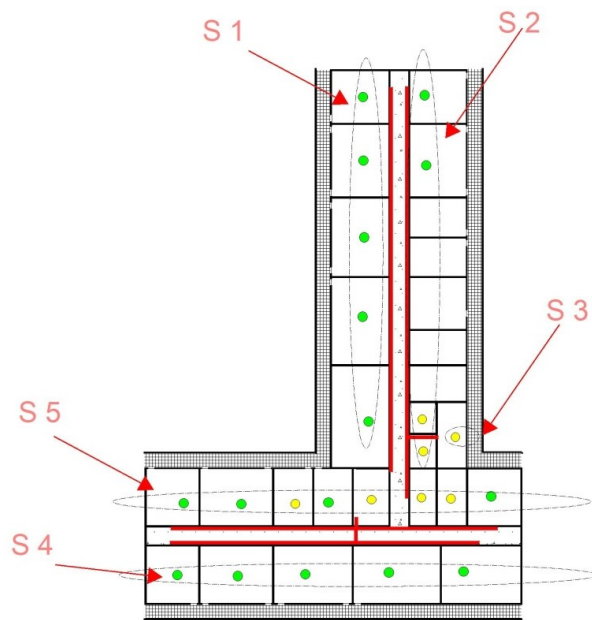


Figure 17; set based representations based on the service adjacency graph

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, a number of 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 in to a Clipper polygon object, proceeds to offset the polygon by a predetermined value, which goes further than the thickness of a standard wall object (Figure 18).

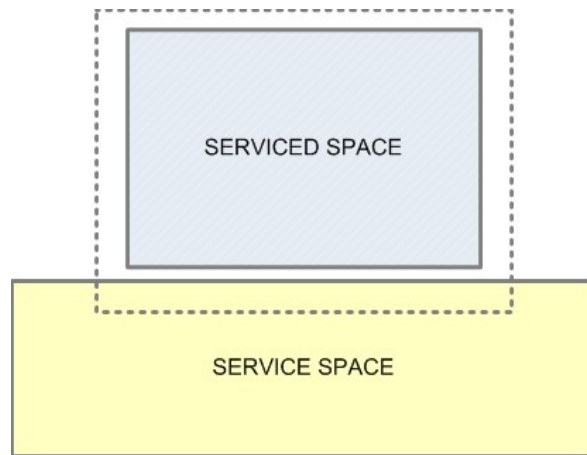


Figure 18 spatial adjacency derivation through polygon offset

To determine the actual adjacency the VREM places a point at the midpoint 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 (Figure 19). 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.

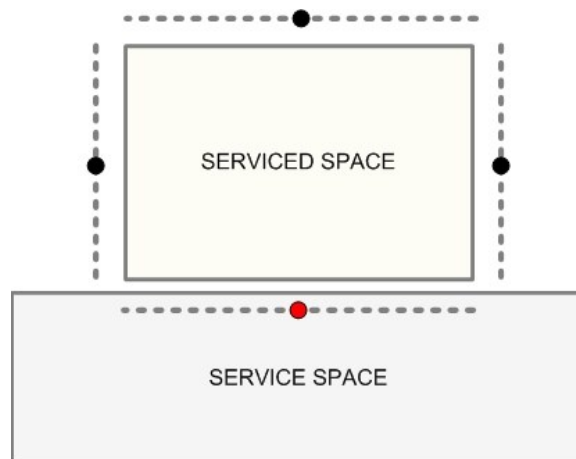


Figure 19 adjacent spaces midpoint derivation

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, if the number is odd then the point is inside the polygon (Figure 20). 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.

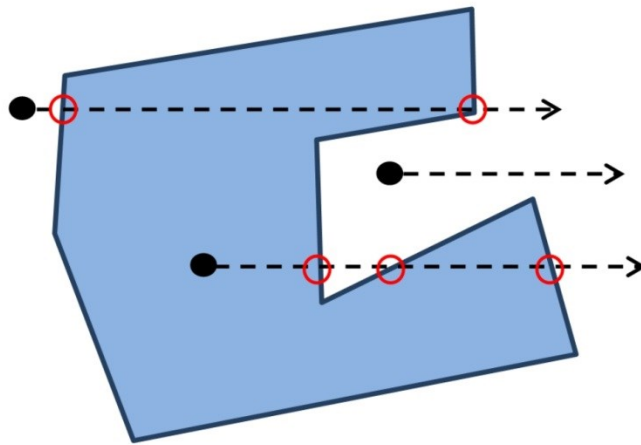


Figure 20 point in polygon test diagram

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.

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 involves also 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.

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 edge 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.

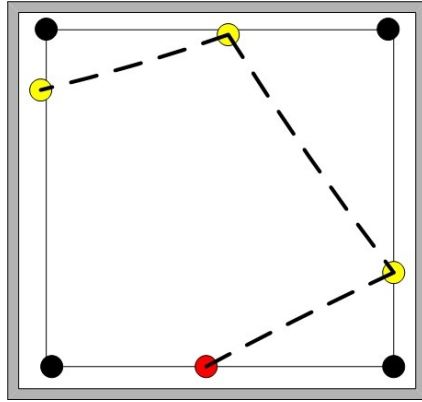


Figure 21 routing of the ventilation duct on convex spaces

This approach which is somewhat easy to evaluate in square shaped service spaces (Figure 21 routing of the ventilation duct on convex spaces), might appear a little bit more convoluted when dealing with more complex layouts (Figure 22 routing of the ventilation on concave spaces).

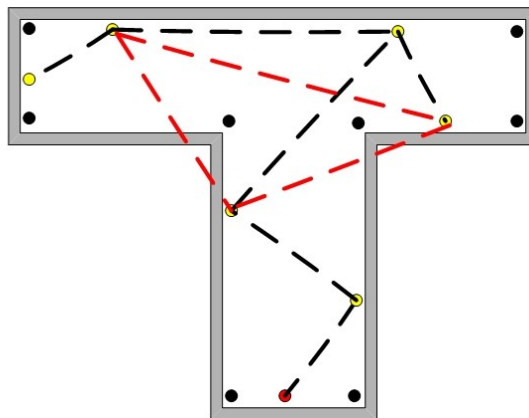


Figure 22 routing of the ventilation on concave spaces

Although the developed approach at first might appear as a non-conventional solution for the routing of the ventilation duct (Figure 23), 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.

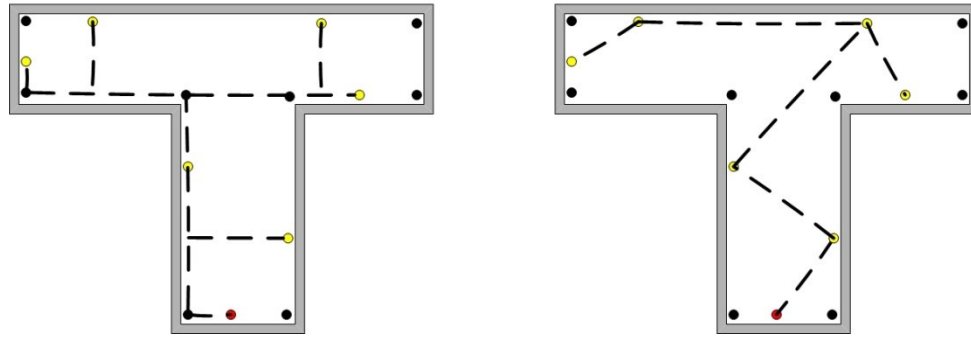


Figure 23 routing of the ventilation duct, red dot indicates start point, yellow dot indicates room connection , and black dot indicates circulation room vertex

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 in to 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 a number of inputs (Jack, 2012). Similar to the approach developed by Jack (2012), 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.

$$t_{loss} = \sum t_{major_losses} + \sum t_{minor_losses} \quad \text{Equation 9}$$

Where:

t_{loss} = total head loss in the pipe or duct system (Pa, N/m²)

t_{major_losses} = major loss due to friction in the pipe or duct system (Pa, N/m²)

t_{minor_losses} = minor loss due to the components in the system (Pa, N/m²)

Retrieving the mayor head loss of a 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 (McIntosh, 2001), 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 material composition of exhausts, this is not the case for the supply system, since is assumed that just fresh air travels through it (McIntosh, 2001) 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:

$$p_{loss} = \lambda \left(\frac{l}{d_h} \right) \left(\frac{\rho \cdot v^2}{2} \right) \quad \text{Equation 10}$$

Where:

p_{loss} = pressure loss (Pa, N/m²)

λ = friction coefficient (k)

l = length of duct or pipe (m)

d_h = hydraulic diameter (m)

ρ = 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:

$$d_h = 4 A / p \quad \text{Equation 11}$$

Where:

d_h = 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:

$$d_h = 4 \pi r^2 / 2 \pi r \quad \text{Equation 12}$$

Or

$$d_h = 2 r \quad \text{Equation 13}$$

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.

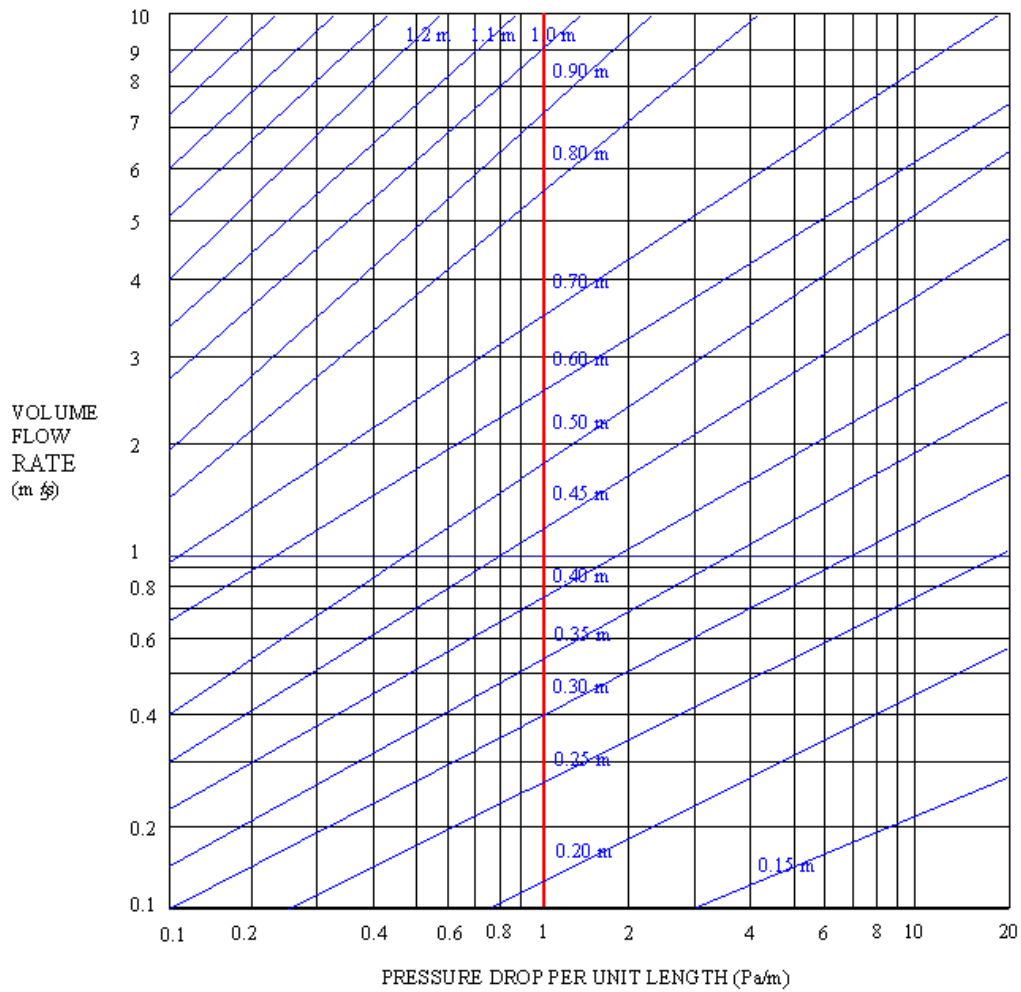


Figure 24: Pressure drops against air quantity or volume and duct diameter.

Table 2 recommended duct sizing

Maximum Air Volume Flow				
		Cubic meter per hour	CFH (cubic feet per hour)	CFM
		Industrial systems	Industrial systems	
		Main ducts	Main ducts	
Diameter	Diameter	Speed M/s	Speed ft. per sec	
<i>(mm)</i>	<i>(inches)</i>	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

After all the pervious 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 of the ventilation system. Therefore 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 system. The defaulting of these takes in to account that for the estimation of the mayor losses in the system, we translated all the possible configurations in to 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 3 minor losse coefficient for common duct components

REM Type	Component or Fitting	Minor Loss Coefficient - ξ -
A	90 ⁰ bend, rounded radius/diameter duct <1	0.5
B	90 ⁰ bend, rounded radius/diameter duct >1	0.25
C	45 ⁰ bend, rounded radius/diameter duct <1	0.2
D	45 ⁰ 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 4), 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/in^2 in to 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.

CHAPTER 5

System evaluation

Although the domain expertise used for the development of the LVDA prototype are based in widely accepted domain specific heuristics (DiBerardinis L et al, 2012; Dahan, 2000; McIntosh, Dorgan et al., 2001; Health, 2003; Chosewood and Wilson, 2007; Facilities 2008; Handbook-Fundamentals 2013) and traditional numerical methods for the design and calculation of HVAC systems (Harris and Conde, 1959; McQuiston, Parker et al., 1994; Dagostino and Wujek, 1995; Todesco, 2004; Sauer, Howell et al., 2005).

The approach defined here for ventilation system engineering has been implemented in a software prototype, this will be evaluated by comparing its results to a traditional BPS tool within the context of a laboratory PCD. Three areas will be evaluated here; cooling load calculation, the ventilation system estimation, and the number of steps needed by the different approaches to produce feedback.

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.

Test model semantics

For the simulation process a test case model was created using Autodesk Revit, the model was developed with PCD level of completion (GSA, 2010). For PCD projects the P-100 requires for the specific definition of: the massing of the building, circulation areas, work spaces, special spaces, mechanical rooms, and service spaces.

Simulation process

The LVDA prototype evaluation process requires for the comparison between traditional PCD ventilation system engineering, and the ventilation system engineering estimation performed by the LVDA prototype. For the evaluation of cooling load calculations, we compare the results generated in traditional process, and the feedback produced by the LVDA prototype. For the purpose of estimation of ventilation system performance evaluation a simulation of the building performance will be conducted using Trane Trace 700, results will be compared to the feedback produced by the LVDA prototype.

Cooling load calculations

The performance evaluation of the LVDA when dealing with the computation of cooling loads, is based in the comparison of efficiency in terms of ease of use and efficiency, between the LVDA prototype and traditional process, for the evaluation we produced detailed business process models (BPM) (Diagram 3: BPM showing the BIM

enabled cooling load computation process (author)) representing the BIM enabled system and the traditional manual process (**Error! Reference source not found.**). From these we analyze both the number of data exchanges, remodeling steps, and UI inputs required from end users in order to obtain the required feedback.

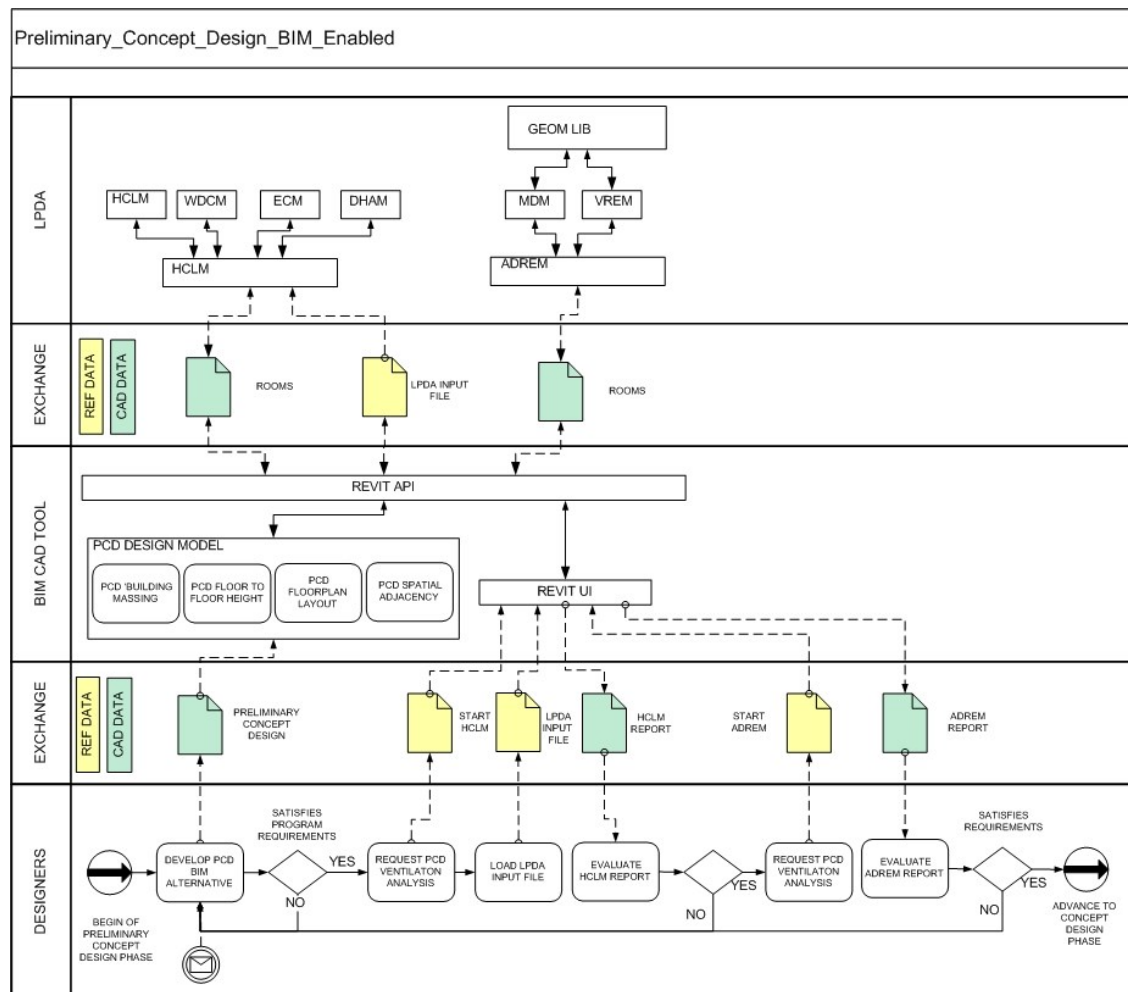


Diagram 3: BPM showing the BIM enabled cooling load computation process (author)

When compared to the traditional process (**Error! Reference source not found.**) to the BIM enabled LVDA system provides several advantages regarding both

ease of use and efficiency; there is a reduced number of user inputs required in order to generate feedback, there are no data exchanges; which increases the accuracy of the calculations, no human reinterpretation of results, the assessment does not interrupt design workflows, and feedback generation can be measured in terms of seconds instead of minutes or hours.

Ventilation system engineering estimation

Modeling approach

For the evaluation process of the LVDA prototype in the area of ventilation system engineering, we have chosen traditional building performance simulation (BPS) software commonly used for this purpose, Trane Trace 700. For the generation of the simulation model we have defined 5 space types (or usages), along with a set of parameters (Table 4), these are used in both Trane Trace 700 and the LVDA prototype when performing the building estimation.

Table 4 space types simulation parameters

Simulation parameters		
Space type	Exchange rate per hour	Internal loads
LABORATORY	6	12.3
LAB. SUPPORT	6	12.3
OFFICE	4	1.3
CIRCULATION	4	1.0
NON VENTILATED	0	1.0

Thermal zones definition

Although traditionally when simulating building performance using BPS, the modeling the thermal zones of buildings is done using a perimeter and core zones

representational model (Figure 25). In this research we have implemented the modeling of all thermal zones based on their space usage (Figure 26). There are two reasons for the implementation of space based thermal modeling in the LVDA prototype:

- It eliminates the processing of the spatial aggregation required by the perimeter and core model, therefore reducing the computing time required for the aggression of the spaces when constructing the zones.
- This approach better represents the PCD layout properties and the possible intricacies of the design.

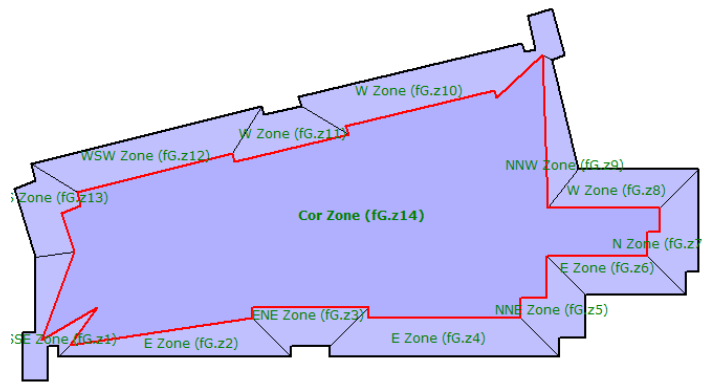


Figure 25: Perimeter and core thermal zone modeling

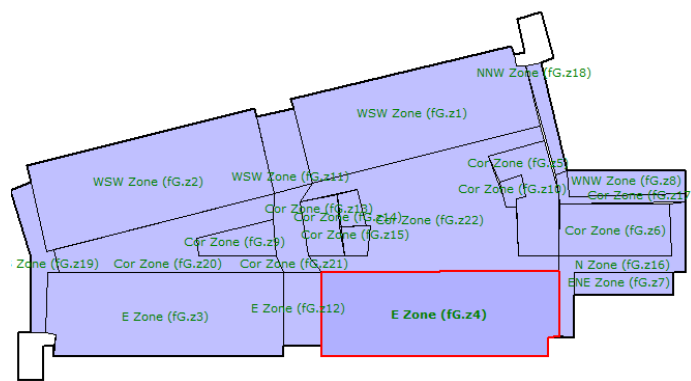


Figure 26: Space usage thermal zone modeling

Building modeling/simulation features

For the purpose of evaluating the results of the LVDA prototype, we have defined a base case for model parameters. These are used both by the LVDA and Trane Trace 700, these parameters consider model attributes ranging from environmental requirements per space type, to building object attributes.

The environmental requirements per space type are identified in Table 4, in it both air exchange rates and the internal heat gains per space are defined, for the properties of the building object properties, and these are defined in Table 5 as follows:

Table 5 Building objects model features

Modeling features	
Building object	Parameter
Walls	6” concrete
Floor	6” concrete
Roof	6” concrete

The modeling of the test case is based on the GSA-P100 definition of PCD, therefore it does not include window or door objects, also no ceiling objects inside spaces just concrete finish, no overhangs or skylights are included the model. Although the previous building features have a great deal of impact in the calculation of internal loads; the traditional model for computation of cooling loads in PCD of laboratories (which the LVDA system duplicates), also disregards these elements for the estimation process, it is based on internal spaces heat gains. In the area of building systems operation the ventilation system is modeled to work 24 hours a day 7 days a week, no diversity is

considered in the modeling. Only one floor of the building was simulated during the calibration process.

Layout features

The model tested is based on a traditional laboratory wing configuration, where the serviced spaces (20) are organized around a double loaded corridor, with a service shaft located at one end of the corridor. The base test model (Figure 27, test model base case, or design alternative one based on GSA P100 modeling for PCD) or alternative one, is 11,702 sqft and has been developed using a traditional orthogonal arrangement of a laboratory wing. Three other design alternatives were also produced with purpose of evaluating the effectiveness of the system to analyze design alternatives. The second alternative layout (Figure 28, test model alternative 2 based on GSA P100 modeling for PCD) splits the corridor into two diagonal corridors (Y shaped) and maintains the same number of spaces. The third layout (Figure 29, test model alternative 3 based on GSA P100 modeling for PCD) replaces the double loaded corridor for a single loaded corridor (L shape) and reduces the number of spaces to 14, but increases the program area of each space instance to match closely the original square footage. The fourth alternative (Figure 30 **test model alternative 4 based on GSA P100 modeling for PCD**) contains the same number of spaces as the third alternative, but one of the wings has been modeled using curved walls, this was done in order to test the efficiency of system when dealing with more complex geometries.

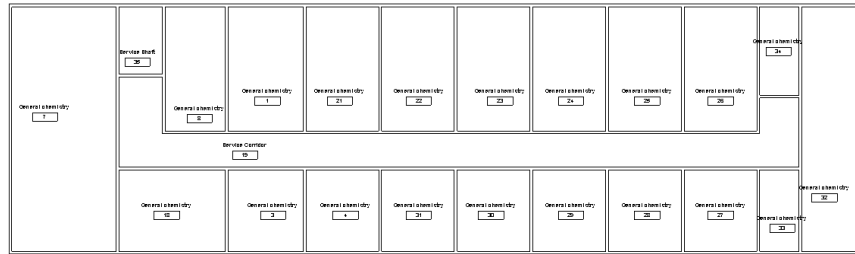


Figure 27, test model base case, or design alternative one based on GSA P100 modeling for PCD

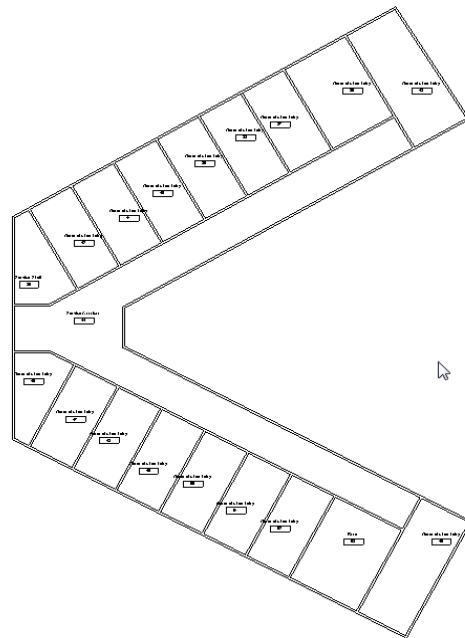


Figure 28, test model alternative 2 based on GSA P100 modeling for PCD

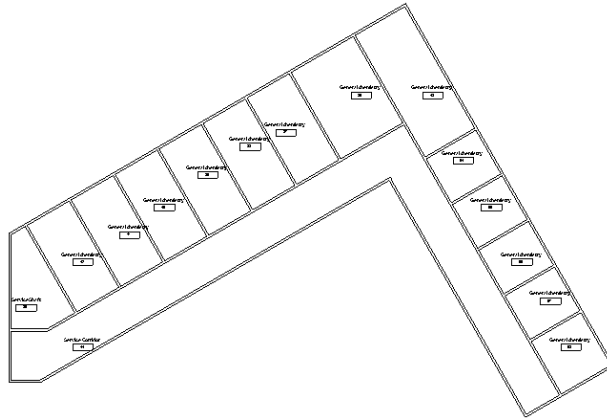


Figure 29, test model alternative 3 based on GSA P100 modeling for PCD

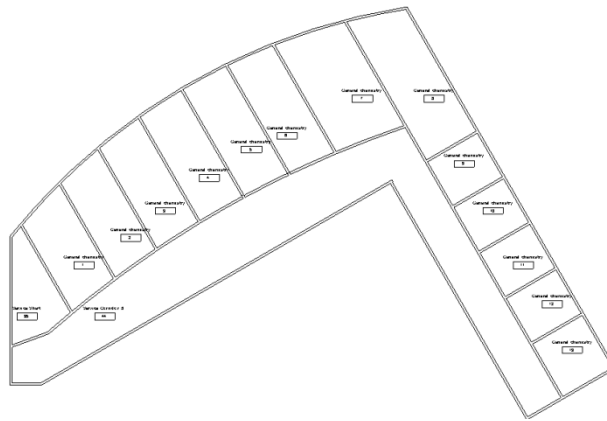


Figure 30 test model alternative 4 based on GSA P100 modeling for PCD


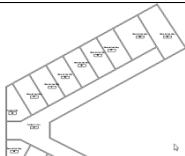
Modeling and system performance estimation

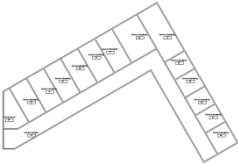
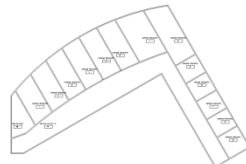
It would take about 10 to 15 minutes to an Autodesk Revit user to generate each of the different layout options defined in the study, and less than 23 seconds to produce ventilation system engineering feedback using the LVDA. In the case of Trane Trace 700 the time the total time for the re-modeling proposed alternatives requires the definition of about 130 parameters (Appendix: A), just the definition of these would take 14 minutes, plus the time it required to extract the geometric properties of each room, which is

incremented proportionally by the number of rooms in the model. In the case of alternative 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 7. Also the user feedback provided by the system can be seen in the following figures; Figure 33, Figure 34, Figure 35, Figure 36, Figure 37, test alternative 3 LVDA system metrics feedback window, Figure 38, test alternative 4 LVDA system route estimation. Notice that each iteration of assessment is indexed in to a text based output file (Figure 46, LVDA text based system summary, for design alternative 1 and 3) 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 to 6.4 minutes to evaluate the impact in the system performance of a design change.

Table 6 LVDA prototype assessment performance

Alternative layout	Modeling type/execution time	Time to produce feedback/ type of feedback
 <p>Base case</p>	<p>model production starting from a new file/11 minutes</p>	22 seconds cooling loads
		1.86 seconds ventilation system estimation
	<p>model production starting form a new file/14 minutes</p>	22 seconds cooling loads

Alternative 1		1.9 seconds ventilation system estimation
 Alternative 2	design alternative starting form alternative 1/6 minutes	18 seconds cooling loads
		1.7 seconds ventilation system estimation
 Alternative 3	design alternative starting form alternative 2/4 minutes	18 seconds cooling loads
		4 seconds ventilation system estimation

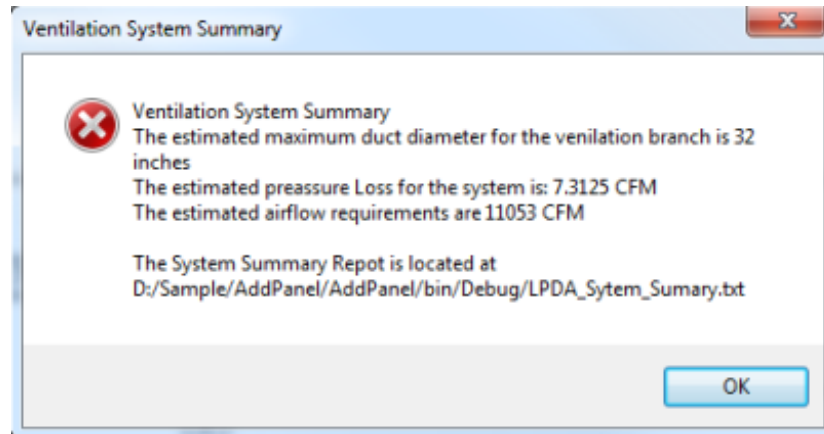


Figure 31 test base case or alternative one LVDA system metrics feedback window

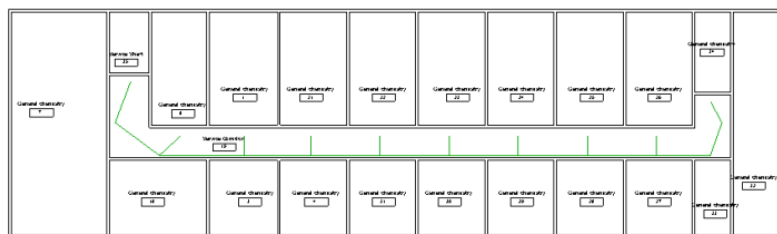


Figure 32, test base case or alternative one LVDA system route estimation

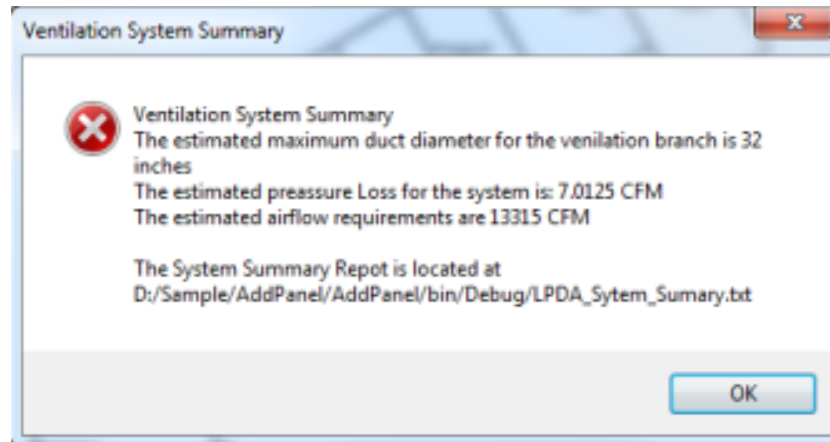


Figure 33, test alternative 2 LVDA system metrics feedback window

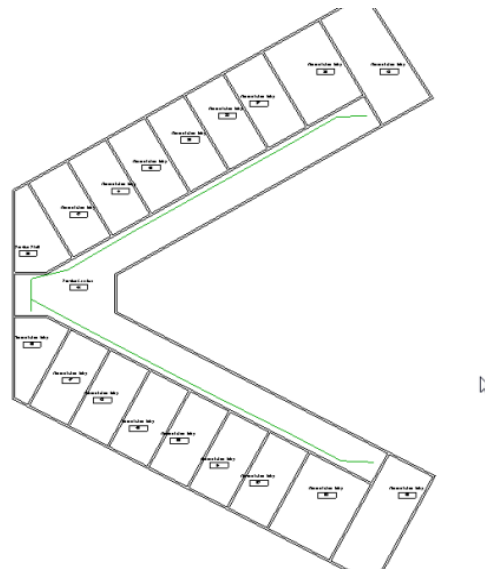


Figure 34, test alternative 2 LVDA system route estimation

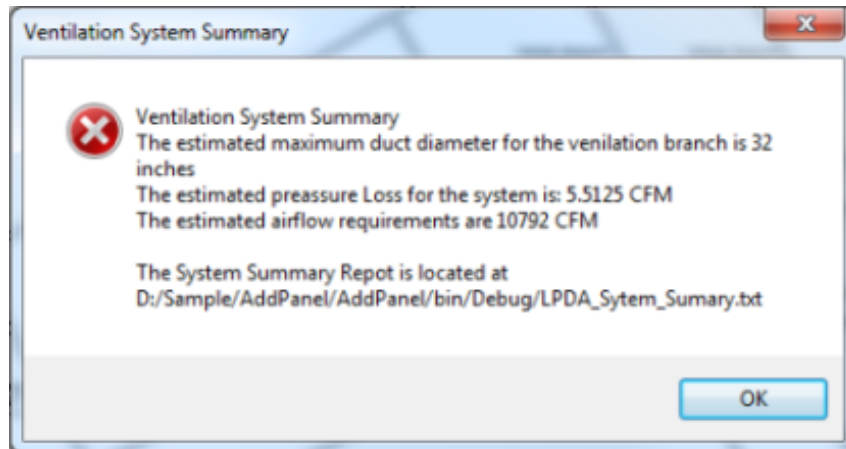


Figure 35, test alternative 3 LVDA system metrics feedback window



Figure 36, test alternative 3 LVDA system route estimation

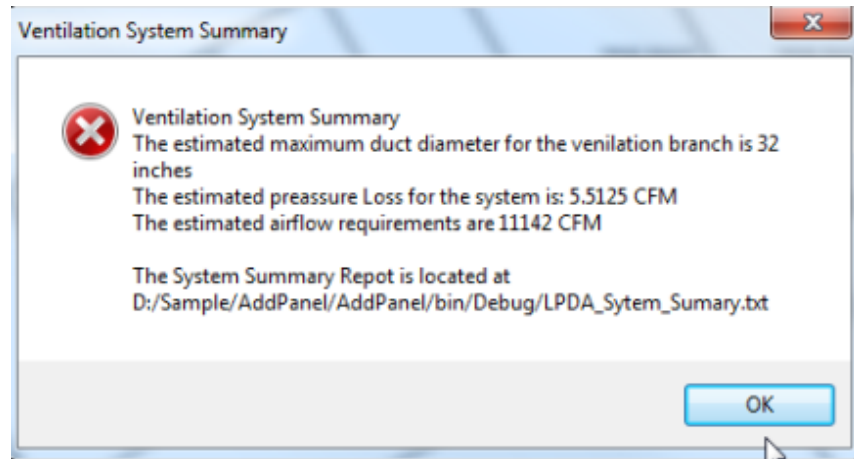


Figure 37, test alternative 3 LVDA system metrics feedback window



Figure 38, test alternative 4 LVDA system route estimation

In the case of Trane Trace 700 although there is a vast amount of simulation parameters that can be reused when analyzing the different design alternatives, changes to the geometry of the layout will require for the simulationist to spend several minutes extracting the geometry information from the model and setting it in the room creation window (Figure 39, Trane Trace 700 wall parameter assignment window), this requires for the manual input of length and orientation of each of the space's bounding wall

objects. The time required to complete this process will vary depending on both the extent of the changes between the alternatives and the geometric features of the walls. The reconfiguration of the simulation for alternatives 2 and 3 takes between 25 to 35 minutes. The time required to complete the simulation modeling becomes longer when dealing with curved walls, as in alternative 4 (Figure 38, test alternative 4 LVDA system route estimation). Trane Trace 700 does not include a mechanism for modeling curved walls therefore it would be up to the modeler to define what the most adequate abstraction for modeling these is, in order to input the information in the user interface of Trane Trace 700 (Figure 40 Trane Trace 700, user interface, wall geometric properties window). Among the abstraction options we would have; tessellating the curve in to straight segments or simply replacing it for a straight element with a specific orientation.

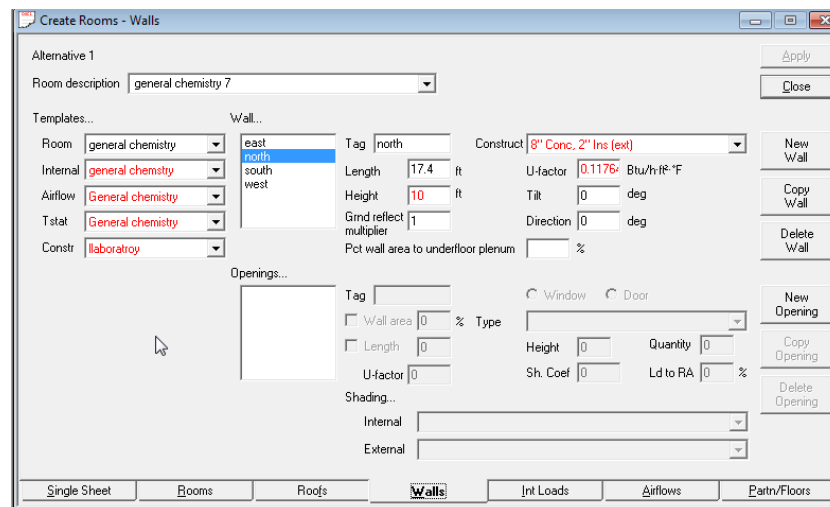


Figure 39, Trane Trace 700 wall parameter assignment window

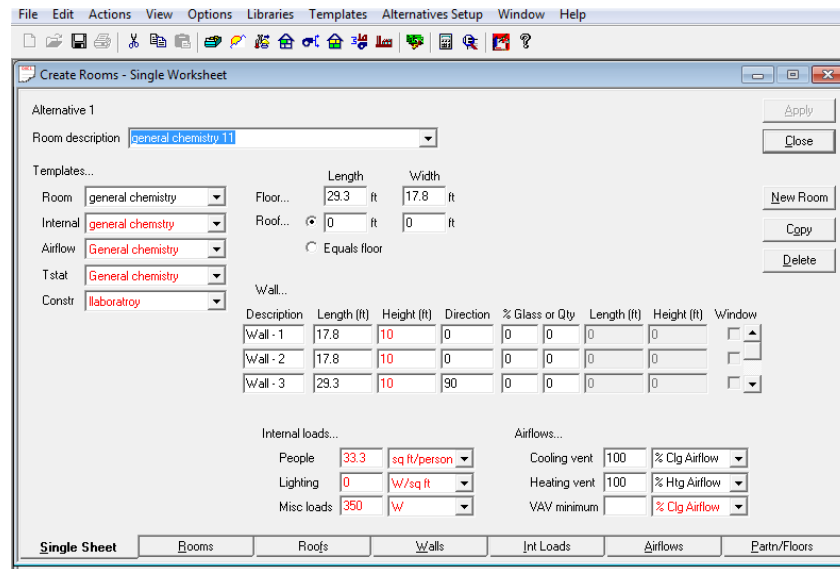


Figure 40 Trane Trace 700, user interface, wall geometric properties window

PCD ventilation estimation and PCD simulation

Many differences can be identified between BIM enabled ventilation system engineering and traditional HVAC estimation when used during PCD. Among these; amount of modeling assumptions, execution speed, feedback semantics, spatial representation accuracy, and consistency.

In the case of the traditional HVAC estimation for PCD, it is required a vast number of domain specific attributes, and the input of geometric properties coming from the design model. The parameters required by Trane Trace 700 for the evaluation process of the alternative designs displayed in figures 27-28-29-30 are detailed in appendix A.

BIM enabled system engineering such as the LVDA prototype, requires only for the selection of the adequate input file, and the specification of project location. All other pieces of data are retrieved automatically from external sources or derived from model

data; the geometry of spaces, thermal zones, construction types, spatial adjacencies, and layout morphology.

Other fundamental differences can be pointed in the areas of; the UI environment and the extensibility of usage of these tools, in the case of traditional approaches for the estimation of HVAC system performance they require for AE's to collaborate in order to impact the quality of design. In most cases this collaboration has been fruitful in later stages of the process such as FCD's or DD's, but it has been somewhat limited in PCD and CD. Researchers have made efforts to better incorporate traditional BPS tools in to early stages of design (Sanguinetti, 2012), in most cases these efforts concentrate in the development of collaborative design for simulation and in the pre-processing of model data in order to automate the BPS process({Bazjanac, 2011; Welle, 2012) .

Comparing results

Although certain aspects of the building performance estimation can be directly compared between traditional BPS and the LVDA prototype, both approaches have clear differences in terms of end user experience and extent of design feedback; on one hand traditional BPS are meant to assess a wider range of performance parameters and to provide the most accurate results possible, there the need for defining a vast number of input parameters and longer execution time required to provide feedback, on the other hand the LVDA prototype uses normative calculations in order to produce close to real time estimation of very specific aspects of laboratory ventilation system engineering performance.

For the assessment of the LVDA prototype we concentrate mostly on the evaluation of both Trane Trace 700 and the LVDA feedback for the engineering ventilation systems for each of the test models.

In the case of Trane Trace 700 the simulation of the test model alternative 1 generates a ventilation requirement of 11.627 CFM (Figure 41 Trane Trace 700 design airflow report.). When estimating the ventilation requirements for the same model with the LVDA tool, the output value is 11.053 CFM (Figure 42 LVDA airflow estimation output). The small difference between the two can be explained as the result of differences in the ventilation requirements set up in either tool. In the case of Trane Trace 700 the ventilation requirements are calculated based on 20 Cfm per person inside the space, both in heating and cooling design. In the case of the LVDA this varies on each of the space usages defined for the project. If we assume the standard precision to be that of the simulation output provided by Trane Trace 700, then the deviation of the LVDA estimation is about 5.5%.

Differences in estimated output between different tools are not uncommon and in certain areas of BPS can be greater than 5% (Lomas, K. 1997), These differences can be attributed to several factors, such as internal errors either at the level of algorithms or programing structure (Lomas, K. 1997), these differences can also appear when comparing the prediction to the actual building performance, Waltz (1992) indicates a 5% as being an adequate difference when comparing the building simulation output and the real building performance.

SYSTEM SUMMARY						
DESIGN AIRFLOW QUANTITIES						
By Trial						
System Description	System Type	MAIN SYSTEM				
		Outside Airflow cfm	Cooling Airflow cfm	Heating Airflow cfm	Return Airflow cfm	Auxiliary System Supply Airflow cfm
Alternative 1						
System - 001	Bypass Multizone	11,627	11,627	11,627	11,627	0
Totals		11,627	11,627	11,627	11,627	0

Note: Airflows on this report are not additive because they are each taken at the time of their respective peaks. To view the balanced system design airflows, see the appropriate Checksums report (Airflows section).

Figure 41 Trane Trace 700 design airflow report.

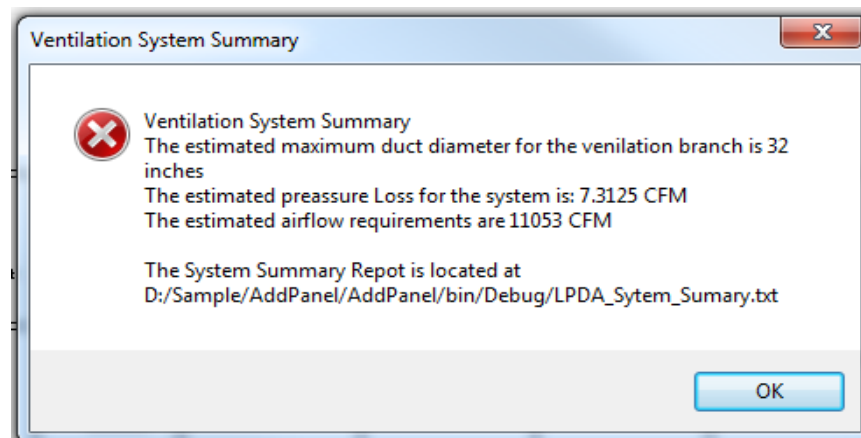


Figure 42 LVDA airflow estimation output

Additional to the ventilation system engineering estimation the LVDA prototype produces additional information that allows designers to better asses the correlation between the architectural layout and the ventilation system components, such as duct diameter(Figure 42 LVDA airflow estimation output) , branch head loss (Figure 42 LVDA airflow estimation output) and routing of the main ventilation duct (Figure 43 LVDA ventilation duct routing estimation.

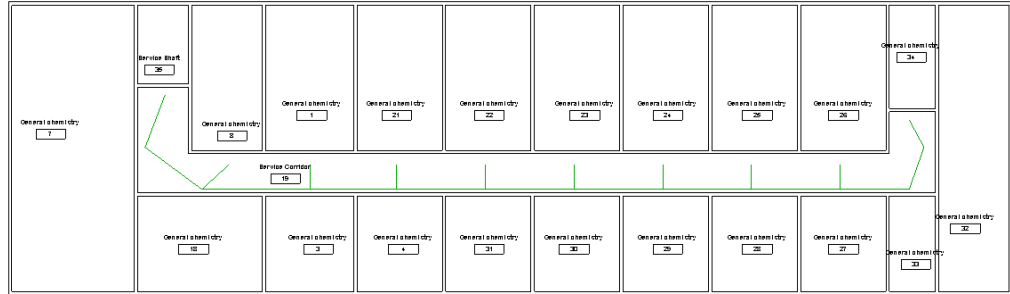


Figure 43 LVDA ventilation duct routing estimation

Alternative designs evaluation.

To support the PCD workflows and decision process, the LVDA prototype has two different mechanisms for illustrating the ventilation system engineering at a close to real time speed: Firstly, the on-screen window ventilation system summary (Figure 44, **LVDA on screen system summary for design alternative 1**, Figure 45, **LVDA on screen system summary for design alternative 3**) which displays the main metrics regarding the engineering of the ventilation system branch and allows for the verification of the impact of design changes in the model. Secondly, the text based summary report (Figure 46, LVDA text based system summary, for design alternative 1 and 3) which aggregates and time stamps each time the estimation process is completed. Therefore, allowing the direct comparison of the system performance between design alternatives. In this case the PCD design alternatives 1 and 3 (Figure 32, test base case or alternative one LVDA system route estimationFigure 36, **test alternative 3 LVDA system route estimation**).

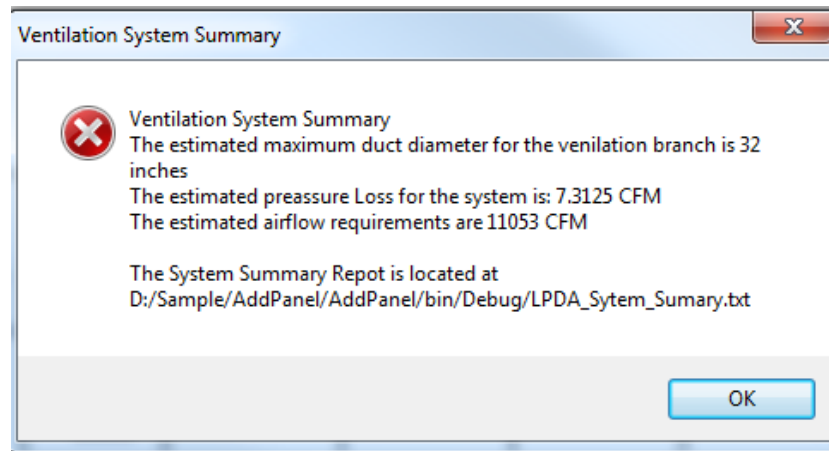


Figure 44, LVDA on screen system summary for design alternative 1

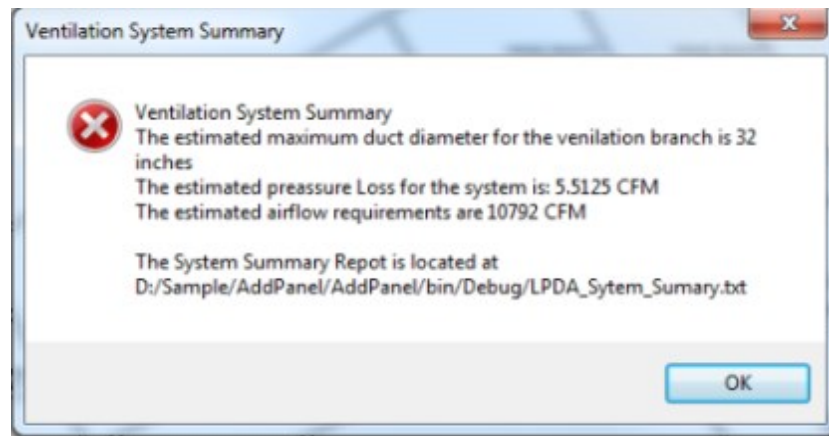


Figure 45, LVDA on screen system summary for design alternative 3

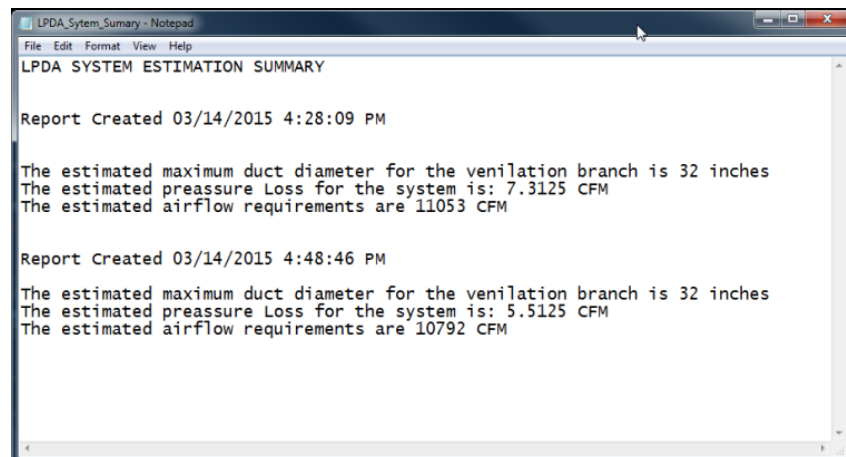


Figure 46, LVDA text based system summary, for design alternative 1 and 3

Limitations

During this study we have identified a number of limitations in the performance estimation for PCD using BIM, these have been classified based on the environment in which they operate and the technologies applied for the implementation.

Limitations given by the application domain

Although the research framework stipulates the limitations of traditional laboratory PCD and that the LVDA prototype has been developed to improve the efficiency of both the estimation and the decision making process within this design stage, it has been evident during the research that extended laboratory building assessment capabilities are feasible: for instance the integration of more accurate representations of heat loads and heat transfers, including both internal and external gains, the estimation of ventilation systems for the purpose of exhaust routing, all these should be possible to include in to the developed framework, with more accurate definition of space usages along with the development and implementation of well-defined rules for the location of laboratory equipment inside spaces.

Limitations given by the implementation approach

Since this research has been conducted within the semantic limitations of laboratories PCD, we have been restricted by these, better accuracy and extended design assistance capabilities could be researched in FCD or DD, although this might carry a higher computational overload, such is the case of the incorporation of material transmittance values of walls and windows objects.

As explained previously there is a strict correlation between model semantics and the capabilities within the LVDA prototype, this define that certain modeling practices or semantics might or might not be supported in the current state of development, here we summarize both modeling practices, facility types, and modeling objects which are supported or not by the LVDA:

Table 7 supported model features

Supported design model features	
feature	reason
Departmental level space aggregations	Input file mapping structure is capable of adjusting to different levels of spatial definition
Multiple layout typologies	LVDA prototype has built in algorithm to deal with complex layouts
Virtual wall objects	LVDA operates based on the space object boundary information no need for wall objects
Custom definition for environmental requirements	Human readable input file allows for easy customization of environmental requirements
Multiple types of service space typology	LVDA has built in a decision tree structure to help the system in the identification of different service space typologies
No doors	Algorithm assumes space access located midpoint of the boundary between the circulation space and the serviced space

Table 8 not supported model features

not supported model features	
feature	reason
wall types	There is no implementation for energy transmittance in current version, only space heat
floor types	There is no implementation for energy transmittance in current version, only space heat
Windows	No implementation of windows locations, these are considered out of the PCD scope
Laboratory equipment	No implementation for equipment locations, these are considered out of the PCD scope
Vivarium	No implementation these are considered out of the

	PCD scope,
Clearstory	No definition for open spaces ranging more than one level in the model
Facilities renovations	There is no provisions in the system for inputting existing ventilation systems nor is the provision for classifying spaces as existing or new construction
Customized specification for ventilation systems	Ventilation system properties has been defaulted
Multiple vertical shafts within the layout	In this case the system requires for the selection of one to be used as starting pint
Undefined space usage in space instances	If space object contains no definition for usage, operation is aborted, warning thrown to end user
Not properly bounded space objects	Space object with no boundary information do not provide the required information to support the required operations

Future work

The approach defined in this research for the development of BIM based ventilation system engineering estimation, could incorporate other functionalities to both extend the range of assistances or the domain of application of the system prototype.

Enhancing the definition of ventilation systems components along with their properties, could support, the use of BIM based ventilation systems engineering in project renovations, where by mapping the existing system it would be possible to assess the system modifications required by the proposed design.

Although the proposed frame work already incorporates the capabilities of mapping ventilation system estimation on to IFC attributes, the possibility of developing a mapping structure capable of constructing well defined ventilation system BIM objects, will allow for better interoperability to MEP design software an in general better support of collaborative design.

CHAPTER 6

Summary and conclusion

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, and the evaluation of energy based building performance in PCD.

There are intrinsic limitations to this research that are given by the nature of BIM CAD models for laboratory PCD, regardless this study developed approaches to improve the semantic quality of the BIM in order 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 the area of PCD input data, particularly when evaluating the types and analysis range of results the 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 understanding 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 the feedback produced

by the different approaches, and how these fit the different stages of design, in other terms what is the right tool for the right design phase

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 tradeoff for wider range of assessment parameters and accuracy of the results.

There is no real tradeoff between the LVDA results 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, and they have been used for the construction of the default configuration of the LVDA prototype, the LVDA input file and the automated mapping software.

Different approaches have been developed in this research to extend the scope of the assessment data of laboratories PCD, among these the capability of evaluating the spatial adjacencies of the building layout in terms of building systems engineering and routing. This type of analysis has been deemed useful for several other areas of PCD

feedback and is easy to foresee a wider range of application of these on either other types of assessments or different types of building systems.

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 prototype 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 have to reduce the speed of the design process so specialists can provide feedback. We also believe this tradeoff 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 In order to proceed with laboratory PCD.

APPENDIX A: Simulation parameters used for Trane Trace 700 simulations

Weather Information

- Atlanta, Georgia

Templates

- Internal loads
 - Description: general chemistry
 - People
 - Type: Laboratory
 - Density: 33.3 sq ft per person
 - Sensible 250 btu
 - Schedule: Cooling Only (design)
 - Workstations
 - Density: 1 workstation per person
 - Lighting
 - Type: Fluorescent, hung below ceiling 100% load in to space
 - Heat gain: 0
 - Schedule: Cooling Only (design)
 - Miscellaneous Loads
 - Type: Microcomputer
 - Energy: 350W
 - Energy meter: electricity
 - Schedule: Cooling only (design)
 - Description: Service corridor
 - People
 - Type: none
 - Schedule: Cooling Only (design)
 - Workstations
 - Density:
 - Lighting
 - Type: Fluorescent, hung below ceiling 100% load in to space
 - Heat gain: 0
 - Schedule: Cooling Only (design)
- Airflow
 - Description: general chemistry
 - ventilation
 - Type: 100% outside air

- Cooling: 6 air changes per hour
 - Heating: 6 air changes per hour
 - Schedule: available 100%
- infiltration
 - Type: none
- Room exhaust
 - Rate: 100% CLG
 - Schedule :available 100%
- Description: Service corridor
 - ventilation
 - Type: 100%outside air
 - Cooling: 4 air changes per hour
 - Heating: 4 air changes per hour
 - Schedule: available 100%
 - infiltration
 - Type: none
 - Room exhaust
 - Rate: 100% CLG
 - Schedule :available 100%
- Thermostat
 - Description: general chemistry
 - Thermostat setting
 - Cooling Dry bulb:75 F
 - Heating Dry bulb: 74 F
 - Relative humidity:55 %
 - Cooling driftpoint:75 F
 - Heating driftpoint:54 F
 - Cooling schedule: Cstat
 - Heating schedule: none
 - Sensor locator
 - Type: room
 - CO2 sensor: none
 - Humidity
 - Moisture Capacitance: medium
 - Humidistat location : room
 - Description: service corridor
 - Thermostat setting
 - Cooling Dry bulb:75 F
 - Heating Dry bulb: 70 F

- Relative humidity:50 %
 - Cooling driftpoint:81 F
 - Heating driftpoint:64 F
 - Cooling schedule: none
 - Heating schedule: none
 - Sensor locator
 - Type: room
 - CO2 sensor: none
 - Humidity
 - Moisture Capacitance: medium
 - Humidistat location : room
- Description: Service corridor
 - construction
 - Slab: 6” HW concrete/Ufact 0.534759
 - Roof: 6” HW concrete 0.15” ins/Ufact 0.42558
 - Wall: 8” HW concrete /Ufact 0.117642
 - Wall partition: 8” HW concrete/Ufact 0.490998
 - Height
 - Wall: 10ft
 - Flr to flr: 10ft
 - Plenum \: 2ft
 - Room type: conditioned
- Room
 - Description: General chemistry
 - Templates
 - Internal load: general chemistry
 - Airflow: general chemistry
 - Thermostat: general chemistry
 - Construction: laboratory
 - Description: Service corridor
 - Templates
 - Internal load: service corridor
 - Airflow: service corridor
 - Thermostat: service corridor
 - Construction: service corridor
- Create rooms (rooms numbers are randomly assigned)
 - General chemistry 7

- geometry
 - 24.8'* 57.8'
 - No windows
- General chemistry 8
 - geometry
 - 14.3* 29.3
 - No windows
- General chemistry 3
 - geometry
 - 17.8'* 19.3'
 - No windows
- General chemistry 4
 - geometry
 - 19.3'* 17.4
 - No windows
- General chemistry 7
 - geometry
 - 29.3* 17.8'
 - No windows
- Service corridor 5
 - geometry
 - 131.1'* 11.3'
 - No windows
- General chemistry 21
 - geometry
 - 29.3'* 17.8'
 - No windows
- General chemistry 22
 - geometry
 - 29.3'* 17.8'
 - No windows
- General chemistry 23
 - geometry
 - 29.3'* 17.8'
 - No windows
- General chemistry 24
 - geometry
 - 29.3'* 17.8'
 - No windows
- General chemistry 25
 - geometry
 - 29.3'* 17.8'

- No windows
- General chemistry 26
 - geometry
 - 29.3'* 17.8'
 - No windows
- General chemistry 31
 - geometry
 - 19.3'* 17.4'
 - No windows
- General chemistry 30
 - geometry
 - 19.3'* 17.4'
 - No windows
- General chemistry 29
 - geometry
 - 19.3'* 17.4'
 - No windows
- General chemistry 28
 - geometry
 - 19.3'* 17.4'
 - No windows
- General chemistry 27
 - geometry
 - 19.3'* 17.4'
 - No windows
- General chemistry 33
 - geometry
 - 19.3'* 9.3'
 - No windows
- General chemistry 32
 - geometry
 - 57.8'* 14.3'
 - No windows
- General chemistry 34
 - geometry
 - 20.8'* 9.3'
 - No windows
- General chemistry 18
 - geometry

- 25.3'* 19.3'
 - No windows
- Assign plants
 - All assigned to one system
- Create plants
 - Cooling equipment
 - Cooling plant:001
 - Equipment tag: air cooled chiller
 - Equipment category: air cooled chiller
 - Equipment type: default air cooled chiller
 - Sequencing type: single
 - Heat rejection
 - Type: MZ packaged rooftop cond fan
 - Heating equipment
 - Heatingplant:001
 - Equipment tag: boiler 001
 - Equipment category: boiler
 - Equipment type: default boiler
 - Energy rate:88.3 percent efficient
 - Hot water pump
 - Heating water circ pump
 - Thermal storage
 - None
 - Equipment schedule: available 100% time
- No utility/misc. accessory
- Assign system coils
 - Cooling plant 001
 - Cooling system 001
 - Main cooling coil
 - Heating plant 002
 - Heating system 001
 - Main cooling coil
 - Main heating coil
 - Preheat coil
- No utility rate defined

APPENDIX B:

Pseudo code developed for the LVDA prototype

HLCM pseudo algorithm

Run HLCM

Open transaction to BIM

Check if "LVDA HVAC data" exist:

 Get SheredParemetersFile in Active Application

If

 LVDA HVAC data exist > exit if/Else condition

 Else

 Run DHAM>create "LVDA HVAC data"

 Run DHAM>dynamic assignment of properties

 Create "LVDA cooling load calculations" schedule

 Create column headers> Level; Name; Cooling load,

 Create "Level" column>in "LVDA cooling load calculations"

 Create "Name" column>in "LVDA cooling load calculations"

 Create "Cooling load" column>in "LVDA cooling load calculations"

 Format "LVDA cooling load calculations" schedule> calculate

 totals on "Cooling load" column.

 Column index=0;

 Row index=1;

 For each Room in BIM

 Get LVDA attributes

```

    Get Room level >"LVDA cooling load calculations" add
    "Level" @ Column index, Row index;

    Get Room Name>"LVDA cooling load calculations" add "Name" @
    Column index+1, Row index;

    Compute cooling load>"LVDA cooling load calculations" add
    "Cooling load" @ Column index+1, Row index;

    Row index+1;

    Column index=0;

    End loop;

Close transaction to BIM

Exit HLCM

```

WDCM pseudo algorithm

```

Run HLCM

Run DHAM

Run WDCM

Get BIM Building Location Property (BLP)

    If BLP is empty

        Request end user for location info

    Else

        Get the location

Check for Internet Connection (IC)

    If IC available

        Run weather file request

    Else

```

Request end user for IC
Run weather file request
Open Weather File (WC)
Calculate representative temperature (min-max) for Location
Get relative humidity for Location
Get atmospheric pressure for Location
Exit WDCM
Return to DHAM

DHAM Pseudo algorithm

Create the place holder for the attributes
Create the parameter group
Get SheredParemetersFile in Active Application
Create SharedParameterGroup on SheredParemetersFile
Set target object for SharedParameterGroup to Rooms;
If group does not exist
 Create group
 Label group "LVDA_HVAC"
Bind the target object to group
Exit

Creating the space attributes
 Get the LVDA.xls
 Read LVDA.xls
 Columnindex= 1
 Rowindex= 0

```

Cell location (Rowindex, Columnindex)

String Param= read Cell_location

Open Group "LVDA_HVAC"

While Param in not empty
    LVDA_HVAC create parameter "Param"
    Columnindex +1

Close    LVDA.xls, LVDA_HVAC

Exit

Assign parameter values to space objects

Get all room objects active application

Get the LVDA.xls

Read LVDA.xls

Columnindex= 0

Rowindex= 0

Cell location (Rowindex, Columnindex)

String Space_Name = read Cell_location

While Param in not empty
    LVDA_HVAC create parameter "Param"
    Columnindex +1

Close    LVDA.xls, LVDA_HVAC

Exit

```

ECM algorithm

```

class EnthalpyCalc
{
    public static double Enthalpy(double MaxTempIn, double
RelativHumIn, double PressureIn)
    {
        double EntahlpVal;

        double HumidRatio;

        double MaxTempInKel = Math.Round((((MaxTempIn - 32) * 5) /
9) + 273.15),2);

        double Pws;

        double TempC;

        TempC =Math.Round(( 0.56 * (MaxTempIn - 32)),2);

        double PowNum;

        PowNum = Math.Round(((77.350 + (0.0057 * MaxTempInKel)) -
(7235 / (MaxTempInKel))),2);

        double eVal;

        eVal =Math.Round( Math.Pow(2.718281828459045, PowNum),3);

        Pws = Math.Round( (eVal / Math.Pow(MaxTempInKel, 8.2)),2);

        HumidRatio = Math.Round(((0.62198 * Pws) / (PressureIn -
Pws)),2);

        double Ha;

        Ha = Math.Round((0.240 * MaxTempIn),2);

        double Hw;

        Hw = Math.Round( ((0.444 * MaxTempIn) + 970),2);

```

```

        EntahlpVal = Math.Round((Ha + (HumidRatio * Hw)),2);
    return EntahlpVal;
}
}

```

SAAM Pseudo algorithm

```

ASA create space list>Possible_targets
ASA create space list>Targets
Read Serviced Space Classification" S_S_C"
Get all Room objects active application
If
    Room Name = service corridor
    Get spatial adjacency for service corridor> add to
Possible_targets
    While Possible_targets is not empty
        If S_S_C  $\supset$  Room Name
            Targets add Room.
        Else
            SAAM create space list>2nd_Targets
            While 2nd_Targets is not empty
                If S_S_C  $\supset$  Room Name
                    Targets add Room.
    If
        Room Name = service shaft

```

```

    Get spatial adjacency for service shaft> add to
Possible_targets
    While Possible_targets is not empty
        If S_S_C  $\supset$  Room Name
            Targets add Room.
        Else
            SAAM create space list>2nd_Targets
    While 2nd_Targets is not empty
        If S_S_C  $\supset$  Room Name
            Targets add Room.
    Exit

```

Prim's Pseudo-Algorithm

$G = (V, E)$ represents a connected undirected graph

$W(e)$ bijection from its edges to their weights

$T = (V_n, E_n)$ graph representing the minimal spanning tree of G

Initial Stage

Select an edge $e \in E$ such that e minimizes $w(e)$. If there is more than one choice, pick out any one arbitrarily. Add e to E_n and add its endpoints to V_n .

Iterative Stage

Select an edge $e \in E - E_n$ adjacent to T such that e minimizes $w(e)$. As before, if there is more than one edge that minimizes

weight, the choice is arbitrary. Add e to E and add the endpoint of e that is not currently in V_n to V_n .

Repeat previous step until $|E_n| = |V| - 1$, i.e. until the minimal spanning tree has one less edge than the number of vertices. This step indicates the algorithm is complete, since a tree with n vertices necessarily has $n-1$ edges.

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Westphal, F. S. and R. Lamberts (2004). "The use of simplified weather data to estimate thermal loads of non-residential buildings." *Energy and Buildings* 36(8): 847-854.

VITA

Academic Education

2006-Present: Georgia Institute of Technology PhD program Design Computing. Atlanta Georgia. USA.

2005: Post Professional Master of Architecture, University Of Southern California, Los Angeles, California, USA.

2002: Professional Architect degree Universidad Maritima de Chile., Vina del Mar, Chile.

1999: Bachelor in Architecture degree Universidad Maritima de Chile, Vina del Mar, Chile.

1988-1990: Advertising Fundacion Duoc Chile, Vina del Mar, Chile.

Academic work

Instructor

2013-14 University of Missouri, College of Human Environmental Sciences, Department of Architectural Studies, instructor; Design communication ArchSt 2230, Architectural Studio 3 ArchSt 4823, Architectural Studio 3 ArchSt 4824, Architectural Studio 2 ArchSt 3182, Programming for Thesis Design Studio ArchSt4860, recent trends in digital media ArchSt4355,

Instructor-teaching assistant

2011-2012: Georgia Institute of Technology, Instructor, class curriculum developer, School of Building Construction, BIM for Building Construction, BC 4803 undergrad level, BC-8803 graduate level.

Fall 2006: Georgia Institute of Technology, School of Architecture, Graduate Teaching Assistant, ARCH 4420 introduction to design computation, Prof. Harris Dimitropoulus.

March - July 2006 Universidad de las Americas, School of Architecture, contemporary architecture theory, substitute instructor.

1997-2004: Universidad Maritima De Chile, School of Architecture, Descriptive Geometrics, Teaching Assistant. Prof. Pedro Eizaguirre

Studio critic

December 2010: University of Kansas, School of Architecture, Guest critic, fifth year studio final studio presentations. Urban intervention in earthquake zone: Haiti. Prof. Paola Sanguinetti.

Fall 2009 Georgia Institute of Technology, School of Architecture, Guest critic, first year studio, final studio presentations.

Fall 2007: Georgia Institute of Technology, School of Architecture, Guest critic, first & Second year studio, final studio presentations.

June 2006: Universidad de Talca, School of Architecture, Guest critic, second and fourth year studio final studio presentations.

Scholarly Presentations

2009 Georgia Institute of Technology, School of Architecture, 5th year Masters Studio class, "The Necessity for Semantically Rich Building Data Models"

2006 Universidad de las Americas, School of Architecture, Inaugural Class, "Kinetics in Architecture: current developments in architectonic organisms".

Research Experience

2010-2012: Georgia Institute of Technology, Research Assistant, Prof Charles M Eastman, GSA PCD building assessment. The project researched the automation of Preliminary Concept Design assessment of US Court Houses in the areas of: Circulation and Security, Space Program Review, Energy Analysis, Cost Estimation.

2007-2009: Georgia Institute of Technology, Research Assistant, Prof Charles M Eastman, GSA automation of Courthouse design. The project researched the automation of Final Concept Design assessment of US Court Houses in the areas of: Circulation and Security.

2009: Georgia Institute of Technology, Research Assistant, Prof Charles M Eastman. GSA-FDA Laboratory design automation. The project researched

the development of computational design assistances for the design of laboratory facilities.

Fall 2007-Summer 2007: Georgia Institute of Technology, School of Architecture, Graduate Mechanical engineer. Georgia Tech Solar Decathlon. In charge of design and implementation of Photovoltaic panels kinetics systems.

Spring 2005-Fall 2005: University of Southern California, School of Architecture, Graduate Research Scholar. Prof. Thomas Spiegelhalter, USC Zero Energy demonstration House.

Fall 2004: University of Southern California, School of Architecture, Graduate Research Scholar. Dean Robert Timme. Reconstruction project of: Frank Lloyd Wright Freeman House.

Conferences

Labs21 annual 2012; The development of the Laboratory Design Assistant, I2SL conference, San Jose, California, October 2-4, 2012, Session B4.

2012 Third Annual GA Tech Digital Building Laboratory Industry Symposium, “Energy Planning in Laboratories”, May15-16, Atlanta, Georgia.

CAAD Futures 2011; Preliminary Concept Design tools for laboratory buildings, automated design optimization and assessment embedded in Building Information Modeling (BIM) tools, Liège, Belgium, 4 - 8 July 2011
2011 Second Annual GA Tech Digital Building Laboratory Industry Symposium, “Embedding expertise in design tools: Preliminary design of laboratories”, Hugo Sheward, May 25-26, Atlanta, Georgia.

CAAD Futures 2009; Using multi-level virtual environments as a medium for conducting design review through a shared IFC dataset. Montreal, Canada, June 17-19 2009.

IASDR 07; Comparing Notes, analyzing teachers' and students' perceived concept importance based on highlighting architecture study documents. Hong Kong, 12-15 November 2007.

Referred Conference Proceedings

Sheward, H., Eastman C., "Preliminary Concept Design tools for laboratory buildings, automated design optimization and assessment embedded in Building Information Modeling (BIM) tools", Proceedings of the 14th International conference on Computer Aided Architectural Design, Edited by Pierre Leclercq, Ann Heylighen and Geneviève Martin, Les Éditions de l'Université de Liège 2011, ISBN: 978-2-8745-6142-9

Swarts M., Sheward H., CAAD Futures 2009; Using multi-level virtual environments as a medium for conducting design review through a shared IFC dataset. Proceedings of the 13th International CAAD Futures Conference. Edited by Temy Tidafti and Tomás Dorta, Les Presses de l'Université de Montréal, Montréal, 2009 ISBN: 978-2-7606-2177-0

Sheward H., Luen Do E.;" Comparing Notes, analyzing teachers' and students' perceived concept importance based on highlighting architecture study documents",. IASDR07 Proceedings, ed. Sharon Poggenpohl (2007). Hong Kong: The Hong Kong Polytechnic University. (The International Association of Societies of Design Research (IASDR) 07, 12-15 Nov 2007, The Hong Kong Polytechnic University, Hong Kong)

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Lee, J.K.; Lee, J.; Jeong, Y.; Sheward, H.; Sanguinetti, P.; Abdelmohsen, S.; Eastman, C.M. (2012). "Development of space database for automated building design review systems." *Automation in Construction* 24: 203-212.

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Magazine (Invited-Article)

Eastman, C. (2009). et al. "Automated assessment of early concept designs.", *Architectural Design* 79(2): 52-57.

Book (invited)

Eastman, C., et al. (2008). BIM handbook: A guide to building information modeling for owners, managers, architects, engineers, contractors, and fabricators, Wiley, Hoboken, NJ.

Kensek K., Noble D. Building Information Modeling: BIM in Current and Future Practice, Wiley, Hoboken, NJ.

Technical publication

Sheward H., (2010), GSA BIM: Guide series 006; Circulation and Security Validation, contain a compendium of best practices and modeling guide lines required to comply with the modeling requirement set forth by the GSA automated circulation and security checking.
<http://www.gsa.gov/portal/content/105075>

GSA BIM: Guide for Preliminary Concept Design Review, Circulation and Security Validation, contain a compendium of best practices and modeling guide lines required to comply with the modeling requirement set forth by the GSA Preliminary Concept Design review process.
<http://www.gsa.gov/portal/content/105075>

Sheward H., (2011), BuildingSmart MVD; Architectural design to Circulation/Security Analysis, defines the Model View Definition to support process defined data exchanges from BIM authoring applications to Industry Foundation Classes 2x3 (IFC2x3) for the purpose of GSA Final Concept Design Circulation and Security Validation
<http://www.blis-project.org/IAI-MVD/>

Sheward H., (2011), BuildingSmart MVD; Early Concept Design to Analysis, defines the Model View Definition to support process defined data exchanges from BIM authoring applications to Industry Foundation Classes 2x3 (IFC2x3) for the purpose of GSA Preliminary Concept Design Assessment. <http://www.blis-project.org/IAI-MVD/>

Awards

Building Simulation 2009; student modeling competition award, First Place. The competition required the development of a control model for a hybrid ventilation system, for a small building located in Glasgow (Scotland).

Fiatech, CETI ;GSA BIM program, Circulation and security analysis modeling application. Awarded the GSA development and implementation of automated BIM-based circulation validation to evaluate the design of

Federal courthouses with respect to security and occupant movement requirements. Automated circulation validation analyzes human movement under various spatial configurations and conditions.

Professional experience

2000-2001 Cristian Alcota architecture; construction site manager for small size retail store, associate designer medium for medium size housing and health care facilities.

1998-1999 Quiroz & Puelma architecture; part of a group participating on a international competition in design. Quinta Vergara Theater, public competition; design of a musical theater and all the annex installations. In charge of the design of all annex buildings.

1994-1997 Algeciras realty company. Modeling artist. In charge of the production of real estate exhibit quality models, ranging from supermarkets, to shopping centers models.

Software Skills expert level user

Computer Aided Design (CAD)

Autodesk Autocad R-14, 2000

Form Z v.4 to v.6.

Rhinoceros 5

Building Information Modeling CAD

Autodesk Revit 2012, 2013 (developer level)

Graphisoft Archicad 12

Vectorworks v8; v9; v10; v11; 2012

Parametric CAD

Dassault Systemes Catia V5.

Gehry Technologies Digital Project V3.

Bentley Generative Components.

Rendering engine

Abvent Artlantis.

3D Studio Max V5; V6; V7

Building simulation

Autodesk Ecotech v5.20

Trane trace 700

Contam

Equest

Industry Foundation Classes building checker

Solibri SMC V5; V6

DDS CAD

4D simulation and

Autodesk Navisworks 2013

Synchro 2012

Software Skills developer level

Building Information Modeling CAD

Autodesk Revit 2012, 2013

Industry Foundation Classes building checker

Solibri SMC V5; V6

Programing languages

Java

C#

Programing environments

Visual studio 2010

Eclipse

Dr. Java

Languages (spoken and written)

Fluent in Spanish, & English