CASE STUDY OF 3D MODELLING AND BUILDING SYSTEM COORDINATION: PROCESS AND KNOWLEDGE

by

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ABSTRACT

Building system coordination is a complicated process that requires the detailed layout and configuration of the various systems such that it complies with design, construction, and operations criteria. Current practice involves an iterative process of overlaying transparent 2D drawings of each system over a light table to identify potential design conflicts and constructability issues, which is a time-consuming and error-prone process. Recent research efforts aim at development of knowledge-based systems to capture, classify, and utilize the specialty knowledge in a retrievable format, and further assist the MEP coordination process.

This thesis presents a case study that investigated the building systems coordination process using 3D models during design and construction of a complex research facility. The objectives of the research were: (1) to document and evaluate the 3D MEP coordination process and (2) to collect and classify the design and construction knowledge utilized in modelling and coordinating building systems.

I modelled and coordinated a variety of building systems in 3D, including architectural, structural, mechanical, electrical, and plumbing systems. I documented the 3D modelling and coordination process, evaluated existing software tools support of this process, documented the resources required to execute this process, and assessed the impact of the 3D models on the coordination process. Over a two-month period, I modelled over 800 m2 of laboratory and corridor space. I identified and resolved 25 design errors, omissions, and inconsistencies, and identified and avoided 25 MEP coordination issues and conflicts.

Throughout this case study, I also identified the design and construction knowledge utilized to create a coordinated and constructable design. I classified this knowledge in a framework instantiated by examples and concepts found in this study. The framework associates the design and construction constraints that govern the modelling and coordination process with the knowledge domain, the domain context, and the specific modelling and coordination task. The main contributions of the research are the evaluation of the 3D coordination process and the identification and classification of building system coordination knowledge.

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DEDICATION

To my parents

and

To the memory of my beloved Hediyeh

ACKNOWLEDGEMENTS

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CO-AUTHORSHIP STATEMENT

The thesis author was responsible for writing the manuscript and coordinating the editorial review process. He performed the literature review, data modelling, data collection, and critical interpretation of the results.

The co-author participated in the development of ideas and was an equal partner with the author in the review and revision of the manuscript.

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CHAPTER 1:
THESIS OVERVIEW

1.1 INTRODUCTION

In a complex building project, coordination of mechanical, electrical and plumbing/process piping (MEP) systems is a critical and challenging task. Building system coordination involves the detailed layout and configuration of the various building systems such that it complies with design, construction, and operations criteria (Barton, 1983; Tatum and Korman, 2000). Specialty contractors are typically responsible for the coordination of MEP systems, including responsibility for checking clearances and identifying routes, fabrication details, and installation locations (Korman and Tatum 2001). Current practice involves an iterative process of overlaying transparent 2D drawings of each system over a light table in a series of MEP coordination meetings focused on critical congested areas. There is limited computer-based support in this process for identifying and communicating MEP coordination issues, developing collaborative solutions, and documenting the results of these MEP coordination meetings. As a result, today's process is time-consuming, error-prone, and often adds significant cost and duration to a project.

In this thesis, I present a case study that investigated the coordination of building systems as part of a 3D modelling process during design and construction of a complex research facility. The project studied was the Chemical and Biological Engineering Building, which is being constructed on the campus of the University of British Columbia (UBC). This facility will provide a variety of teaching and research spaces for the study of biological, chemical, environmental and process engineering at UBC. Developing a coordinated and constructable design was a key concern in this project as it had complex MEP systems.

I modelled and coordinated a variety of building systems in 3D, including architectural, structural, mechanical, electrical, and plumbing systems, in support of the

MEP coordination process. This provided me with a unique opportunity to collect specific and detailed MEP coordination knowledge, since I was actively involved in the 3D coordination process rather than observing the process from the periphery. I classified this MEP coordination knowledge in a framework instantiated by examples from the case study. This framework associates the design and construction constraints that govern the modelling and coordination process with the knowledge domain, the domain context, and the specific modelling and coordination tasks. The main contributions of this research are the evaluation of the 3D coordination process and the identification and classification of the building systems coordination knowledge.

This chapter describes the literature review, the research objectives, and the research methodology. It concludes with a summary of the manuscript.

1.2 LITERATURE REVIEW

For this research, I reviewed the literature in the following areas: 1) Constructability information collection and classification, 2) MEP coordination, and 3) 3D CAD modelling for construction.

1.2.1 Constructability Information Collection And Classification

The Construction Industry Institute (CII) defined constructability as "the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives" ("Constructability", 1986). Another definition is given by the Construction Management committee of the Construction Division of the American Society of Civil Engineers (ASCE) as "The application of a disciplined, systematic optimization of the procurement, construction, test, and start-up phase by knowledgeable, experienced construction personnel who are part of a project team" ("Constructability" 1991).

Research in the area of constructability has covered a range of topics. Many research efforts have focused on broad constructability concerns (Tatum 1988; Fischer 1991; "Constructability" 1991). Others have also developed different classification schemes for constructability knowledge (Hanlon and Sanvido 1995; Fischer and Tatum

1997). Fischer and Tatum (1997) used five categories to store and classify the design-relevant constructability knowledge: application heuristics, layout knowledge, dimensioning knowledge, detailing knowledge, and exogenous knowledge. This framework primarily captured the impacts of constructability concepts on design.

Hanlon and Sanvido (1995) extended this framework to classify constructability information throughout all phases of construction. This framework was grouped into design rules, performance, resource constraints, external impacts and lessons learned. They pointed out that such a classification scheme should: (1) be able to store any technology or experience related information in a retrievable form to the user; (2) handle concepts needed for any process which requires constructability knowledge; and (3) it should be capable of linking to any product classification or coding system. They also suggested that based on the literature and industry, "people describe constructability knowledge in terms of the product being constructed and the processes affected." I believe a very important aspect of constructability is the concept of constructability knowledge relevant to coordination (as a process) of MEP systems (as a product).

1.2.2 MEP Coordination

Korman and Tatum (2001) define MEP coordination as "the arrangement of components of various building systems within the constraints of architecture and structure." Tatum and Korman (2000) conducted a study on the MEP coordination process. They identified MEP coordination knowledge that was relevant to design, construction, and operations and maintenance. They investigated the current process and suggested the need for a revised work process based on a 3D model. They emphasized the need for full visualization capabilities as a requirement of effective MEP coordination, which allows sections cut at any point and direction. They also suggested the use of a composite 3D CAD model that combines preliminary designs for each system. Further research was conducted to develop a framework to represent MEP coordination knowledge in a computer tool (Korman et al. 2003). They classified the types of interferences detected in MEP coordination and provided a reasoning structure to give advice based on the type of interference.

1.2.3 3D CAD Modelling For Construction

Research has demonstrated the benefits of 3D modelling for design coordination and constructability analysis, cost estimating, and construction planning (e.g., Staub-French and Fischer 2001). Other studies demonstrate the advantages of using 3D visualization in construction projects (Rodriguez, 1992; Mahoney et al, 1990; Euler, 1994; Ganah and Bouchlaghem, 2001; Songer et al., 1998).

Rodriguez (1992) defines visualization as the creative ability to form mental images. Limited use of 3D CAD for coordination and design of building systems was found by Mahoney et al (1990). Euler (1994) described the advantages of using 3D CAD plant models as a construction management tool on the construction job site. In this study, he described how a 3D CAD model can be used as a "communication medium" to promote input from contractors. Other researchers have indicated the impacts of 3D Walk-Thru visualizations on the construction scheduling process (Songer et al. 1998; Staub-French and Fischer, 2001). They demonstrated a reduction in missing activities and relationships as well as a reduction in invalid relationships in a schedule. Finally, Ganah and Bouchlaghem (2001) explored the use of visualization tools to communicate design intent. In this research, they analyzed the results of an industry survey, which evaluated the potential use of computer visualization to communicate constructability information between designers and constructor teams on site.

1.3 Research Objectives

The research objectives on this project were:

1) *To document and evaluate the 3D MEP coordination process*

Throughout this research, I documented the 3D modeling and coordination process, documented the resources required to execute this process, and assessed the impact of the 3D models on the coordination process. This case study provided a unique opportunity to test the capabilities of 3D modeling tools for interference detection and conflict resolution in building system coordination, since I was actively involved in the 3D coordination process rather than observing the process from the periphery.

2) *To collect and classify the design and construction knowledge utilized in modeling and coordinating building systems.*

I identified the design and construction knowledge utilized to create a coordinated and constructable design. To represent MEP coordination knowledge, it is necessary to understand the different constraints that govern the design and construction of these systems and how those constraints relate to model development and coordination. I classified this knowledge in a framework instantiated by examples from the case study. This framework associates the design and construction constraints that governed the modeling and coordination process with the knowledge domain, the domain context, and the specific modeling and coordination tasks.

1.4 METHODOLOGY

The methods that were used to achieve the research objectives include the following:

1. *Literature Review:*

I reviewed the available literature in the area of MEP coordination to identify the body of knowledge which I could use and build upon in the case study. In addition, the literature review helped me to identify what was missing in these studies and how my research could contribute to this body of knowledge. This formed a solid background for performing the case study, as well as the point of departure for my research. I also reviewed the literature of classification schemes and knowledge frameworks in the construction domain which helped to establish the basis for my data analysis and classification.

2. *Evaluate State-of-the-art 3D Software*

Throughout the first couple of weeks of this case study, I learned and worked with Autodesk Building Systems 2005, which was the state-of-the-art software in the industry. This gave me a better understanding of current available tools, and enabled me to perform the case study.

3. *3D Modeling and Data Collection*

   To develop and coordinate 3D models of the project, I reviewed the 2D drawings and project documents, observed the design coordination meetings, and collaborated with the architect and consultant of the project. This enhanced my understanding of building systems components, and the current practice and procedures governing the coordination process. I developed the details and modeled a variety of systems including: architectural, structural, mechanical, plumbing and electrical systems.

4. *3D Coordination and Knowledge Collection*

   In order to coordinate the developed 3D models of the building systems I communicated the conflicts and issues in coordination meetings and one-on-one discussions with designers, subcontractors and specialty trades. Using the 3D model as a visual collaboration tool to find the optimum workable resolution, I collected and stored data on the constraints, governing the coordination process.

5. *Data Analysis and Knowledge Classification*

   I classified the collected knowledge by building on and extending existing knowledge frameworks found in the literature. Our goal in developing this framework was to formalize the MEP coordination knowledge I collected in a way that conveys the context of the knowledge, represents the generality of the knowledge, enables reuse of the knowledge across multiple projects, and potentially supports computer-based implementation.

1.5 THE MANUSCRIPT OVERVIEW

The next chapter presents a research paper submitted for publication to the Canadian Journal of Civil Engineering for the special construction issue. In this paper, I present the details of this case study. I first introduce the project and explain the characteristics of this unique opportunity. Then I explain the 3D modelling and coordination process and present some examples of the issues and conflicts identified. The complete details of the case study, which describe the 3D modelling process and conflicts identified in more detail, were documented in a separate report that was submitted directly to the project team. This report is presented in the appendix of this thesis. The paper then describes how I analyzed and classified the collected data based on the results of this case study and the available knowledge frameworks found in the literature. I classified this knowledge in a framework that associates the design and construction constraints that govern the modelling and coordination process with the knowledge domain, the domain context, and the specific modelling and coordination task. This classification extends existing knowledge frameworks by representing the construction perspective in more detail, and relating the MEP coordination knowledge to specific modelling and coordination tasks.

Next, in the concluding chapter, I present the results of this research. I describe the resources required to execute a 3D MEP coordination process on an actual project, the benefits of 3D modelling for MEP coordination, and the lessons learned. In addition, I discuss my conclusions and provide suggestions for future research.

1.6 BIBLIOGRAPHY

Barton, P.K. (1983). *Building Services integration*, E & FN Spon, London

"Constructability: a primer." (1986). *Publication 3-1*, Construction Industry Institute, Bureau of Engineering Research, University of Texas at Austin, Texas.

"Constructability and constructability programs: White paper." (1991). *J. Constr. Engrg. Mgmt.*, ASCE, 117 (1), 67-89.

Euler, J.K., (1994). "Advantages of using 3D CAD plant models on the Construction site." *Microcomputers in Civil Engineering*, 9 (6) 435-444

Fischer, M. (1991). "Constructability input to preliminary design of reinforced concrete structures.", *Technical Report No. 64,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Fischer M., and Tatum, C.B., (1997). "Characteristics of Design-Relevant Constructability Knowledge." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 123 (3) 253-259.

Ganah, A., Anumba, C.J., and Bouchlaghem, N.M., (2001). "A survey of visualization tools to communicate buildability information." *COBRA 2001 conference*, Glascow, 2-4 September, pp.721-731 (available at www.rics-foundation.org)

Hanlon, E.J., and Sanvido, V.E., (1995). "Constructability Information Classification Scheme." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 121 (4) 337-345

Korman, T.M., Fischer, M., and Tatum, C.B., (2003). "Knowledge and Reasoning for MEP Coordination." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 129(6) 627-634.

Korman, T.M., and Tatum, C.B., (2001). "Development of a Knowledge-Based System to Improve Mechanical, Electrical, and Plumbing Coordination." *Technical Report No. 129,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Mahoney, J., Tatum, C. B., and Kishi, K. (1990). ''Construction site applications of CAD.'' *Technical Report No. 36*, Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Songer, A.D., Diekmann, J., and Al-Rasheed, K. (1998), "The Impact of 3D Visualization on Construction Planning", *Proceedings of the International Congress on Computing in Civil Engineering*, ASCE, Reston, VA.

Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration.", *Technical Report No. 122,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Tatum, C.B, (1988). "Classification system for construction technology." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 114 (3) 344-363.

Tatum, C.B., and Korman, T. M., (2000). "Coordinating Building Systems: Process and Knowledge." *J. Arch. Engrg.*, ASCE, New York, NY, 6 (4) 116-121.

CHAPTER 2: MODELLING AND COORDINATING BUILDING SYSTEMS: A CASE STUDY[1]

2.1 INTRODUCTION

In a complex building project, coordination of mechanical, electrical and plumbing/process piping (MEP) systems is a critical and challenging task. Building system coordination involves the detailed layout and configuration of the various building systems such that it complies with design, construction, and operations criteria (Barton 1983, Tatum and Korman 2000). Specialty contractors are typically responsible for the coordination of MEP systems, including responsibility for checking clearances and identifying routes, fabrication details, and installation locations (Korman et al. 2001). Current practice involves an iterative process of overlaying transparent 2D drawings of each system over a light table in a series of MEP coordination meetings focused on critical congested areas. There is limited computer-based support in this process for identifying and communicating MEP coordination issues, developing collaborative solutions, and documenting the results of these MEP coordination meetings. As a result, today's process is time-consuming, error-prone, and often adds significant cost and duration to a project.

Recent advancements in 3D modelling tools have been shown to significantly improve the building systems coordination process (e.g., Staub-French and Fischer 2001, Songer et al. 1998). Current 3D modelling technologies, such as Autodesk Building Systems, provide pre-defined objects that facilitate the development, routing, and connection of MEP systems in a 3D model, and provide conflict detection mechanisms that help to identify physical interferences. Recent research efforts have developed knowledge-based systems that take advantage of such rich product models to support the MEP coordination process. For example, Korman et al. (2003) developed a knowledge-

[1] A version of this chapter has been submitted for publication: Tabesh, A., and Staub-French, S., Canadian Journal of Civil Engineering (CJCE), Special Construction Issue, 2005.

based system that represents design, construction, and operations knowledge of MEP systems, identifies potential conflicts, and suggests solutions. Our research seeks to build on these efforts by extending the breadth and depth of MEP coordination knowledge represented with particular emphasis placed on representing the construction perspective.

Our long-term research goal is to improve the constructability of facility designs through the development of richer, more robust model-based tools that facilitate interference detection and conflict resolution in the design and coordination of MEP systems. To represent MEP coordination knowledge, it is necessary to understand the different constraints that govern the design and construction of these systems and how those constraints relate to model development and coordination. This case study is an example of such an attempt to gain a better understanding of the design and coordination of MEP systems in the context of a 3D modelling and coordination process on an actual project. Specifically, our research objectives on this project were: (1) to document and evaluate the 3D MEP coordination process and (2) to collect and classify the design and construction knowledge utilized in modelling and coordinating building systems.

The project studied was the Chemical and Biological Engineering Building, which is being constructed on the campus of the University of British Columbia (UBC). This facility will provide a variety of teaching and research spaces for the study of biological, chemical, environmental and process engineering at UBC. The building systems of this project were complex and accounted for a large part of the total project cost. We modelled and coordinated a variety of building systems in 3D, including architectural, structural, mechanical, electrical, and plumbing systems, in support of the MEP coordination process. This provided us with a unique opportunity to collect specific and detailed MEP coordination knowledge, since we were actively involved in the 3D coordination process rather than observing the process from the periphery. We also had the complete support of the owner of the project and the project team. They not only volunteered their time and knowledge on a daily basis for ten weeks, but they also funded this task and provided the necessary tools and trainings. As a result of their commitment and support, we benefited from active participation of consultants, subcontractors, and foremen on and off the site. In the end, we modelled approximately 800 m^2 of laboratory and corridor space, identified 25 design errors, omissions, and inconsistencies, and avoided 25 MEP coordination issues and conflicts.

This paper describes the 3D modelling and coordination process, the software tools support of this process, the effort required to execute this process, and the impact of the 3D models on the coordination process. It also describes the design and construction constraints that governed the modelling and coordination process, and the classification of this knowledge in a framework instantiated by examples from the case study. This framework associates the design and construction constraints that governed the modelling and coordination process with the knowledge domain, the domain context, and the specific modelling and coordination tasks.

We built on and extended the knowledge framework developed by Korman et al. (2003) to classify the documented constraints. To the best of our knowledge, this is the only time that their work has been applied to classify the knowledge captured from an MEP coordination process on an actual project. The knowledge classification in this case study denoted a validation of their work, and improved it by developing and identifying further knowledge attributes, especially in the construction domain. It also enhanced their framework by revealing the correlation of each constraint, not only with a particular knowledge domain, but also with a coordination task which provides the context for that constraint.

In this paper, we first provide a brief overview of relevant literature. We then describe how we developed and coordinated the 3D models of the MEP systems in the case study. Finally, we discuss the framework we developed to classify the MEP design and coordination knowledge collected from the case study.

2.2 Related Research

Tatum and Korman (2001) define MEP coordination as "the arrangement of components of various building systems within the constraints of architecture and structure." In their research, they investigated the process and knowledge of coordinating building systems, which was the most extensive study to date that we found on MEP coordination. They developed a knowledge framework to represent MEP coordination knowledge and implemented this knowledge in a MEP coordination tool that identifies conflicts and suggests solutions (Korman et al. 2003). The framework represents MEP coordination knowledge for the three domains of design, construction, and operation and maintenance. This knowledge framework was our primary point of departure and provided an excellent starting point to classify the MEP coordination knowledge collected from our case study. We built on and extended this framework to represent the construction perspective in more detail, and to relate the MEP coordination knowledge to specific modelling and coordination tasks.

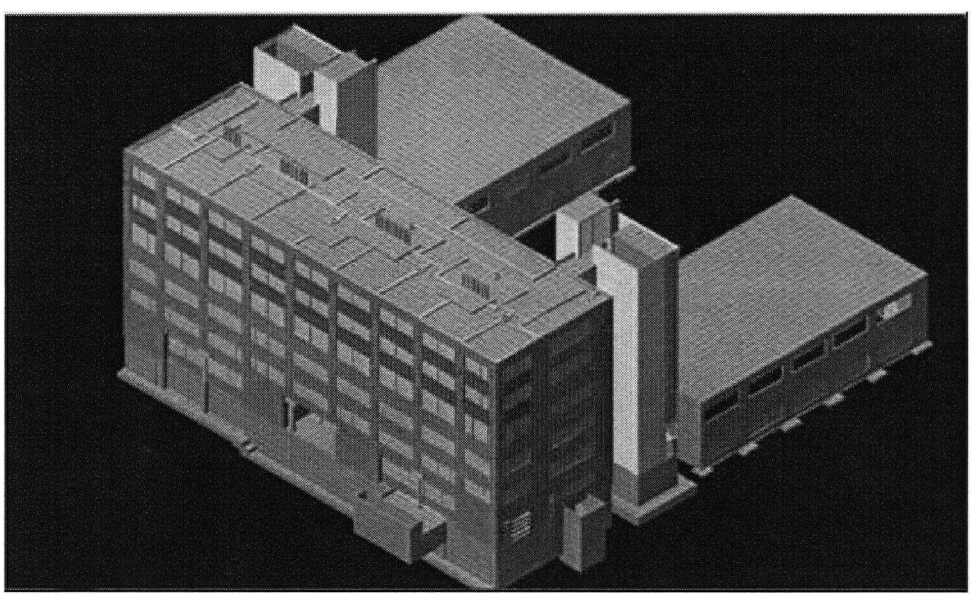
To represent the construction perspective more thoroughly in the MEP coordination process, we reviewed the literature in the area of constructability focusing on information collection and classification. The Construction Industry Institute (CII) defines constructability as "the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives" ("Constructability" 1986). Many research efforts have focused on identifying and classifying constructability knowledge (e.g., Tatum 1988, Fischer and Tatum 1997, Hanlon and Sanvido 1995). We utilized this research to identify and represent specific constructability considerations as they relate to the MEP design and coordination process, which included safety concerns, productivity impacts, fabrication details, and construction tolerances. Hanlon and Sanvido (1995) recognized that "people describe constructability knowledge in terms of the product being constructed and the processes affected." We also represent the concept of constructability knowledge relevant to MEP design and coordination (as a process) of MEP systems (as a product). Specifically, we relate the building system (i.e., the product) to the specific design and coordination task (i.e., the process) for each of the knowledge items (i.e., the domain context).

To represent the MEP design and coordination process, we identified the primary tasks utilized in modelling and coordinating the various building systems. Korman et al. (2003) identified five classes of solutions used to resolve MEP coordination problems: detailing, layout, positioning, application and scheduling. These solution classes provided an excellent starting point for representing the modelling and coordination tasks executed in this case study.

2.3 CASE STUDY

This case study focused on the Chemical & Biological Engineering Building project (Chem-Bio project) under construction at The University of British Columbia (UBC). The project budget was approximately $38M and the construction schedule was 13 months. This facility will provide a variety of teaching and research spaces for the study of biological, environmental and process engineering at UBC. The 123,000 square foot building will include high-head laboratories, teaching/research laboratories, large lecture theatres; offices, seminar rooms, project rooms, undergraduate facilities; and shops, storage and support rooms. These spaces have been grouped for functional and adjacency reasons into two distinct structures: Laboratories, offices and lecture theatres have been grouped in a six storey structure. The high-head laboratories, attendant support spaces and workshops are housed in a low-rise, ground-related structure for service access and structural loading reasons. Figure 2.1 shows a 3D model of the Chemical & Biological Engineering Buildings.

Figure 2.1: 3D Model of Chemical and Biological Engineering Building Project



The project team consisted of representatives from different parties involved in the project: the owner, UBC Properties Trust; the architect, Bunting Coady Architects partnering with Diamond and Schmitt Architects Inc.; the construction manager/general contractor (GC), Stuart Olson Construction Ltd.; the mechanical subcontractor/ project manager, Daryl-Evans Mechanical Ltd.; the plumbing subcontractor/project manager, IMEC Mechanical Ltd.; and the electrical subcontractor/project manager Bridge Electric Corp.

We became involved in this project at the request of the owner's representative and project manager. He asked us to help evaluate the feasibility of using 3D models for building system design and coordination. He saw the potential of 3D modelling and wanted to test it out in a small-scale pilot study on the Chem-Bio project. If the pilot study was successful, he intended to use a 3D design process on future projects at full scale. As a result, the other parties involved in the project were eager to participate and be involved in this task, so that they could be involved in potential future projects as well. The owner and general contractor provided the funding for this research and the architect provided the hardware, software and technical support for the computer tools. Early in the project, we were located in the architect's offices so that we could get immediate support in understanding the design and creating the 3D model of the project. The contractor provided the on-site office location and facilitated the participation of subcontractors and foremen in the project. The project team was committed to the 3D design process and participated actively throughout the course of the project.

We worked with the project team over a two month period to develop detailed 3D models of all the building systems in several critical spaces. We used Autodesk Building Systems software (ABS), because the architect and the consultants had already developed their 2D drawings in AutoCAD and because ABS offers an integrated MEP-Architectural application. In addition, ABS provides much of the engineering data needed in a library of standard predefined objects (e.g. walls, doors, windows, ducts, pumps, valves, etc.).

We followed the guidelines provided in the literature that suggested revising the coordination process using a 3D CAD model to combine separate CAD files (Korman et al. 2001). In this process, by analyzing the composite model, the MEP coordinator can identify physical interferences and non-compliance with different design, construction and operation constraints. In addition, the model can provide separate drawings and design views of the MEP systems by different specialty contractors, during and after the coordination process.

The following sections describe the process for developing and coordinating the integrated 3D model, and the design conflicts and constructability issues identified.

2.3.1 Develop Integrated Models

We focused our modelling effort on the layout and arrangement of the systems in the corridors and laboratories, which were critical spaces that were of particular concern to the project team. The team was concerned with whether the corridor ceiling spaces were deep enough to contain the necessary MEP systems. The project design team had recently reduced the floor-to-floor height of some floors as a "cost saving" measure. Of particular concern were the highly congested MEP areas, including corridors connecting to the laboratories and risers, elevator shafts, and the laboratories. We modelled some sections of the corridors on the first, second and sixth floor and created a comprehensive model of a typical lab located on the fifth floor. Figure 2.2 shows the integrated 3D model of a typical lab on the fifth floor of this project.

Figure 2.2: Integrated 3D model of a typical lab on the fifth floor

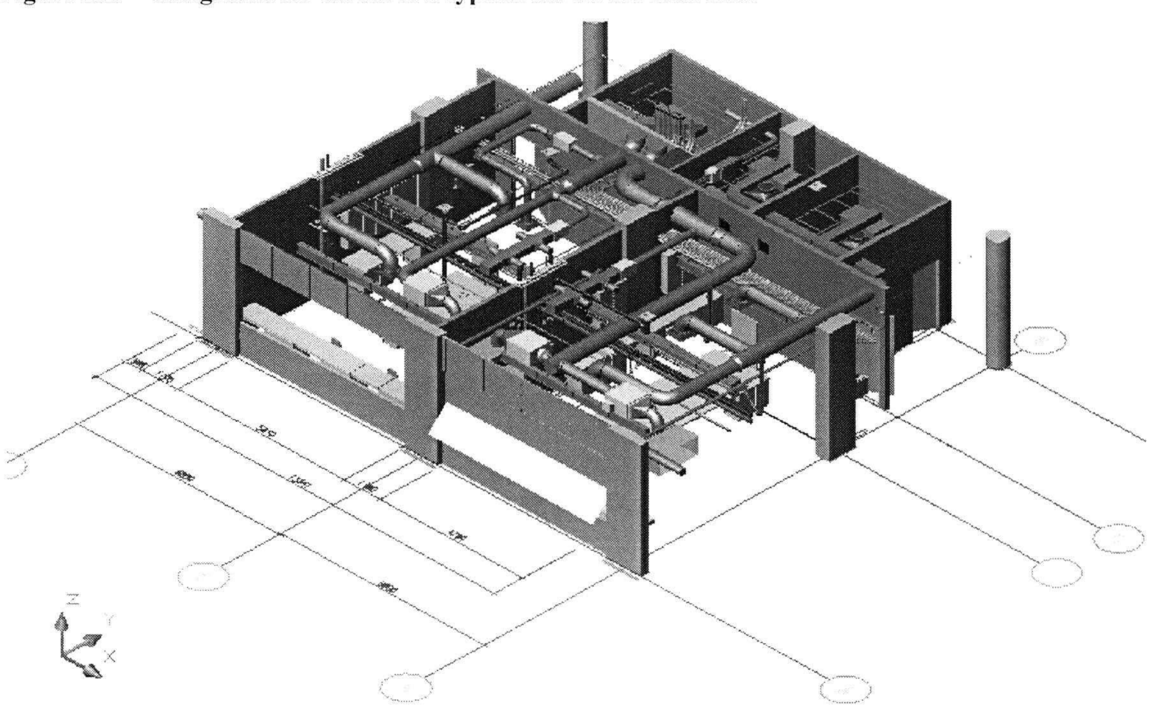
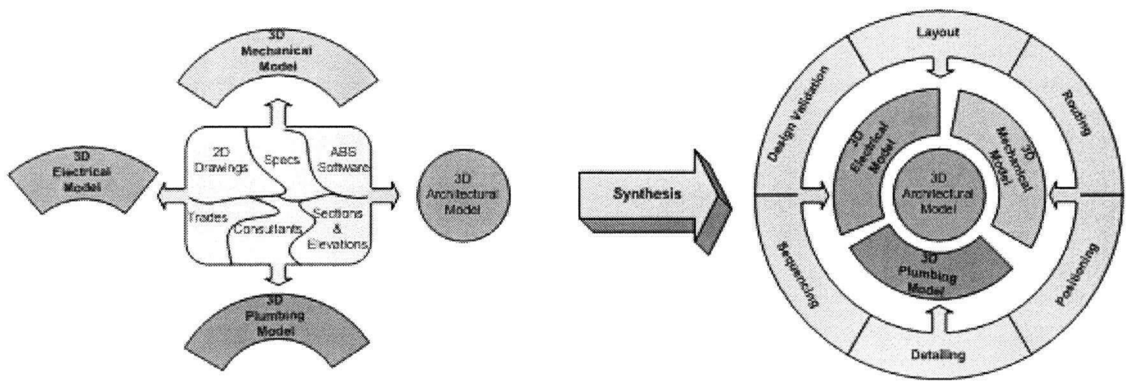


Figure 2.3 illustrates the process for developing the integrated model. We developed the 3D models based on the architect's 2D drawings, which included a conceptual layout of the MEP systems, together with sections and elevation drawings. We also used the drawings of the engineering consultants, together with project specifications that contained more detail on various systems. And finally, we gathered additional information based on detailed discussions with the architect, engineering consultant, and MEP trades. Using ABS software, we used the information gathered from these resources to create 3D models of the individual systems (Figure 2.3a). The coordination process starts with synthesizing every component into the individual system, and then systems into a model (Figure 2.3b).

Figure 2.3: Process for developing the integrated 3D model



a) Resources to develop individual 3D models

b) Modeling and Coordination tasks & integrated 3D coordinated model of MEP systems

This process involves the following modelling and coordination tasks:

- *Routing* of uniform, linear components, such as piping, ductwork and conduits.
- *Positioning* of non-linear components, such as equipment.
- *Layout* of the components where shape, orientation, and coordination matters, such as cable trays and duct fittings.

- Determining the *detailing* of the components which involves developing the design in more detail, such as identifying the fabrication details of a duct fitting.
- Developing the *sequencing* and arrangement of components, such as installing the hot water line on top of the ductwork.
- *Validating the design* assumptions, such as the necessity of a Rain Water Drain line in a specific location.

These tasks were the basic components for developing a solution and resolving interferences in the model. They provided the context in which the attributes of the components of our systems would satisfy the constraints of architectural, structural, and other building systems. The result was a coordinated, integrated 3D model of all the components and systems that fit together without any conflicts and considering constructability concerns

2.3.2 Develop the 3D Architectural Model: Setting the Boundary Condition

To facilitate the 3D MEP coordination process, the first step was to create a 3D model of the architectural systems from the architect's 2D model. The synthesis and modelling of all the architectural components clarified any inconsistencies between design information available in different drawings and sources. To develop the 3D model of the architectural systems, we considered three major groups of elements:

- *Structural Elements:* Columns, beams, concrete walls, slabs and slab openings. The information regarding these elements was extracted from the structural drawings and schedules.
- *Architectural Elements:* Walls, wall openings, ceilings, doors, and windows. Architectural drawings and specifications were the main source of information for these elements.
- *Interior Design Elements:* Casework, extension arms and appliances, such as fume hoods.

Modelling the structural elements was the first step, followed by the architectural design and finally interior design elements. For the first two groups of elements, the relevant data and information were extracted from the 2D floor plans, elevations, sections and project specifications. However, the design for interior design elements was schematic, and assumptions for these elements needed to be made and clarified while modelling.

The synthesis of these three groups of elements clarified any inconsistencies between the design information available in different drawings and sources. We found that the information regarding the floor to floor elevations in the floor plans was not consistent with the same information presented in the elevation plans. In addition, the measurement given for the elevation of the top of the beams in the structural 2D drawings was approximately a foot higher than what the architectural elevations required. Lastly, to represent the service space, the integrated 3D architectural model delineated the spatial boundaries for the 3D model of the MEP systems.

2.3.3 3D Modelling and Coordination of the MEP Systems:

We began modelling the MEP systems based on the available 2D drawings: the architect's 2D drawings, which included a conceptual layout of the MEP systems, and engineering consultant's drawings which contained more detail on various systems. However, these drawings lacked the necessary data for modelling purposes. Most importantly, the layout, positioning and routing of elements within the MEP drawings were defined schematically, and traditionally, left to the judgment of subcontractors to make it work during construction. These characteristics (e.g. elevation, clearance from the wall, etc.) together with details of fittings and equipment had to be determined and clarified when developing a 3D model. We acquired some "layout-knowledge" through discussions and correspondence with the architects, engineering consultants, and MEP trades. Nevertheless, it was still necessary to make some assumptions regarding the layout of the elements, and then test the validity of these assumptions using the 3D model.

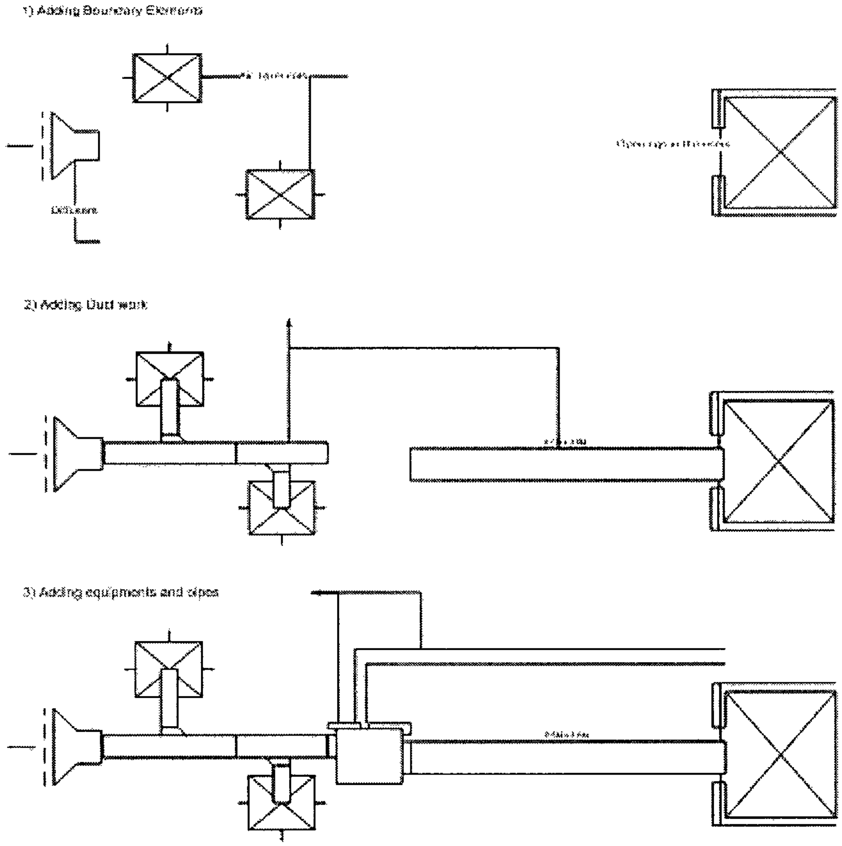
We modelled the MEP subsystems in the order of their coordination. We began with the mechanical systems first because its elements were the least flexible, and occupied the most space.

2.3.3.1 Mechanical Systems:

The mechanical systems included HVAC supply ducts and fittings, exhaust/return ducts and fittings, air terminals, variable air valves (VAVs), coils, mechanical piping, fume hoods and exhaust fans. The size, material and shape of the ducts and fittings together with the size, material and connection type of the pipes and the elevation of air terminals were extracted from the 2D drawings and specifications. However, the elevation of all other elements together with the information regarding the routing and positioning of the entire mechanical systems was defined schematically. Modelling these elements in a 3D environment provided us the opportunity to design the layout of the systems well before its construction by input through one-on-one discussions with the project team and specialty subcontractors.

Figure 2.4 describes the steps for modelling the mechanical systems. Using ABS, we first modelled the air terminals and equipments. These elements and the mechanical system entry point on each floor (such as an opening in a riser) were constrained by the architectural elements. These constraints provided a range for the elevation of the starting and ending elements of the system. The exact elevation was assumed within this range, only to be tested and validated as the model progressed. We then modelled the ductwork, which connected the boundary units. We had to make many assumptions regarding the usage of proper duct fittings and transitions, because in current practice, these details are left to the subcontractors to work out. In addition, we made educated assumptions regarding the minimum clearance of the ductwork from the walls, slabs and ceilings.

Figure 2.4: Three Steps for Modeling the Mechanical Systems



We then modelled the VAVs, and coils which were connected to the ducts. We had to assume dimensions of these elements based on their functional capacity. And finally, we modelled mechanical pipe runs. Layout and routing of the pipe runs and their proper elevation was constrained by the architectural design, design codes, and the positioning of ducts, VAVs and coils. All design assumptions were validated during the coordination meetings.

Through discussions with the subcontractors and the project team, we acquired the necessary knowledge to coordinate the layout and positioning of the mechanical system in the 3D model. Table 2.1 provides examples of resolved conflicts and interferences for coordinating the ductwork and Table 2.3 provides examples of collected modelling and coordination constraints that govern mechanical systems. After all the mechanical systems were modelled in 3D, we created the 3D model of the plumbing systems.

2.3.3.2 Plumbing Systems:

Plumbing systems modelled in this project included the sanitary waste and ventilation system, rain/storm water drain system, domestic cold/hot water systems, natural gas system, compressed air and lubricated compressed air system, and fire protection. The fire protection system was only schematically designed. For the rest of the systems, the size, material and connection type of the pipes and systems was extracted from the 2D drawings and specifications. However, the information regarding the routing, positioning and elevation of the pipe runs were schematic. We designed the layout of these elements based on discussions with the project team and specialty subcontractors.

The approximate layout and schematic routing of the pipes were based on the plumbing drawings. The routing of the plumbing pipe work was constrained by the architectural boundary conditions that include positioning of the plumbing fixtures, the positioning of the risers and vertical stacks, and the available service area above the corridors and labs to provide the horizontal passage between risers and fixtures. The elevation of the pipe-runs and the exact layout and detailed routing of the pipes had to be assumed, modelled and then evaluated to satisfy the boundary conditions and design codes, together with the coordination of other trades. This was especially critical with the gravity-pipe systems like the RWD (Rain-Storm Water Drain) system where the minimum slope of the pipe has to be maintained through out the system. The assumptions were also evaluated to comply with the constraints set by interaction with the other modelled systems.

Sometimes the constraints governing the different systems were contradictory. For instance, while modelling the Rain Water Drain (RWD) system pipes on the 6th floor, we noticed a conflict which had to be resolved. The routing of the four inch RWD line could not go higher than a certain level [+3000 above finished floor (AFF)] as it would interfere with the ductwork, and it could not go lower than a certain level (+2850 AFF) as it could not cross below the ceiling space elevation of an office. In addition this pipe had to run about 10 meters in the service space along the corridor and had to maintain a minimum slope of 1%, as a code requirement. The assigned service space of 150 mm could not satisfy these design-specific requirements. The situation was exacerbated by another constraint imposed by construction variances: the four-inch nominal diameter of the pipe designed in the system was actually larger by almost an inch in reality. We also had to consider additional space for connections and joints, insulation, placeholders, and a margin of construction error. It was easy to visualize the possible solutions and test their validity against the mentioned constraints using the 3D model: we changed the routing of the pipe to avoid the office space, removing one of the boundary constraints. This minor architectural change was made at no cost, and allowed us to assign the necessary space and resolve the conflict.

Once all the elements of all the plumbing systems were modelled satisfactorily in the 3D environment and in coordination with the rest of the plumbing systems, it was time to add the electrical systems to the model.

2.3.3.3 Electrical Systems:

The last systems modelled in this process were the electrical systems. The subsystems considered in this modelling exercise included cable trays, conduits, lighting systems, and electrical panels. The layout of the lighting system and electrical panels were extracted from the architectural 2D drawings and specifications. In the laboratories, we modelled the electrical panels first as they dictated the point of origin of conduits. In corridors, we modelled the lighting fixtures based on the 2D architectural reflected ceiling plans and discussion with the architects. The design aesthetics required keeping them as close as possible to the centre line, but they were also constrained by the layout and routing of the mechanical and plumbing systems.

The electrical 2D drawings contained the information regarding cable trays and conduits. The drawings indicated the size of cable trays and some of the conduits, but contained only schematic information about the layout of these elements. In the 2D electrical drawings of laboratories the conduits were not displayed anywhere. The necessary data and information regarding the size, path and spacing between conduits were all extracted during the one-on-one discussions with the electrical subcontractor. This was also true for modelling the cable trays. We worked with the subcontractors to design the layout of the cable trays. This design had to comply with constraints imposed by the architectural design, clearances required by code and specification, together with the layout of other MEP systems.

In one example, while modelling the typical lab in 3D, we observed that there was not enough space for the conduits to pass through a riser adjacent to the lab, where they had to go through before entering the electrical room at the floor above. A series of large exhaust ducts in the above-the-ceiling riser would prevent the passage of the conduits. The electrical subcontractor indicated that a change of path in conduits is not possible due to a construction code: the number of maximum 90 degree elbows from start to finish for a conduit is limited (four in this case). To provide a solution, we had to make changes in the architectural layout of the riser and the surrounding rooms and spaces, which were easily modelled, validated, and then implemented in the design. Another controversial example occurred when modelling the corridors. UBC electrical construction specifications required a 30 cm vertical clearance on top and a 60 cm horizontal clearance on one side of the cable trays, specifically to provide access for future inspection, maintenance and replacements. It also called for a 15 cm clear zone on top of the cable tray at all times for safety concerns. This constraint imposed a lot of limitations on the actual available service space for the rest of the MEP components in the corridors since we realized the cable tray requires a space twelve times what was originally assumed prior to the modelling task.

2.3.4 Coordinate the Integrated 3D Model

In each of the previous steps, the resulting 3D model of each system was more coordinated than the original 2D model. This was due to the fact that the design, construction and operational considerations were implied and realized throughout the 3D modelling process. However, they were mostly considered individually. The software enabled us to work on separate views when developing each model, facilitating focus on each individual system at a time, and avoiding overcrowding of the model.

Once each model was fully developed, we integrated the systems in a single project view, which allowed the study of interferences between different systems. The software was capable of detecting the physical interferences (also referred to as 'hard conflicts') between components of different systems. However, other types of interferences (i.e. 'soft conflicts') concerning issues like access (e.g. the ductwork intruding the access space of the cable tray), or functionality (e.g. a series of conduits blocking the air terminal and the air flow) could not be identified by the software. Resolving interferences between different systems often required collaboration between two or more specialty subcontractors or designers. To facilitate such collaboration, coordination meetings were set to present the 3D model to the project team and MEP project managers.

In these meetings, the 3D model was displayed on a projector and the respective issues were communicated and described by means of presenting different 3D and 2D views of the model and walkthroughs visualizing the virtually constructed systems. The model allowed each member of the team to visualize the perspectives and concerns of the other specialty trades. The model also allowed the team to test different suggestions, and prompted the trades to come up with workable resolutions in a timely manner. In some instances, the changes and suggestions made in these meetings were implemented in the model spontaneously. In most other cases, they had to be carefully examined after the meeting to make sure that they would not create other conflicts. In any case, these suggestions and changes were agreed on and documented in the meetings and the model was revised based on these coordination decisions. This step was repeated as necessary as design development is an iterative process. However, we believe 3D modelling could reduce the number of iterations.

Figure 2.5 illustrates how ABS presents the detection of hard conflicts (i.e. physical interferences). The software detected interferences between the conduits and the supply duct (left) and its air terminal/diffuser (right). Each figure consists of two views: the 3D solid view on the left, and the 2D plan view on the right. ABS highlights these interferences in the 2D plan view. Note that the conduits were not modelled in the architect's 2D drawings. The presence of conduits was the result of implementing the electrical subcontractor's understanding and point of view of the data available in the design. If this had not been communicated in the 3D model, this knowledge would remain implicit until the execution of the conduits. By that time, the already-fabricated and installed ducts would likely need to be removed and possibly re-fabricated to make room for the conduits.

Figure 2.5: Hard conflict between the conduits and ductwork (left), and between the conduits and the air terminal/diffuser (right)

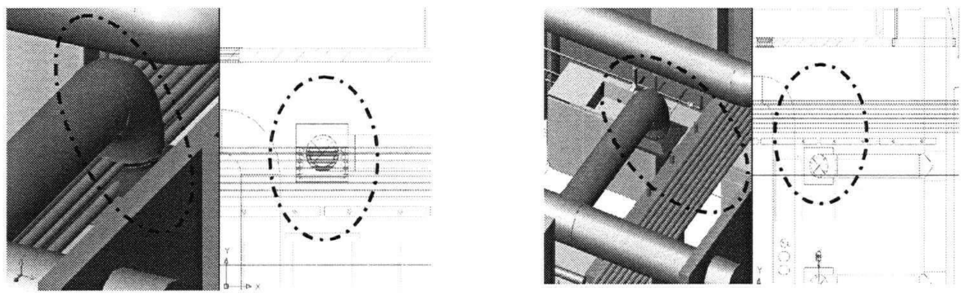
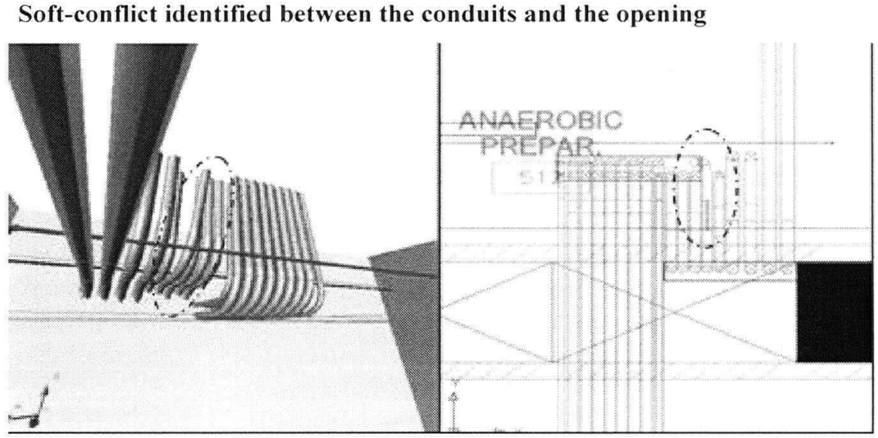


Figure 2.6 shows a soft interference identified in the routing of the conduits. The spacing and curves had to be adjusted so that all the conduits fit into the opening. As the figure illustrates, the software does not show or highlight any interference. Nevertheless, based on the discussions with the electrical subcontractor, we realized that the size of this opening is restricted by the specifications of pre-ordered equipment and could not be enlarged under any circumstances. Considering the minimum possible spacing between the conduits, and the number of conduits that had to fit in this opening, one of the conduits would be left out in the current design.

Figure 2.6: Soft-conflict identified between the conduits and the opening



2.3.5 Case Study Results

On this project, we modelled approximately 800 m2 of laboratory and corridor space over a two-month period (Staub French and Tabesh 2004). We identified and resolved 25 design errors, omissions, and inconsistencies, and identified and avoided 25 MEP coordination issues and conflicts. Table 2.1 provides a summary of some of the interferences detected in this case study.

Table 2.1: Summary of interferences and coordination issues identified in the case study

Description of Interferences and Issues Identified	Interfering Components	
	A	B
Chilled Water/ Heat Recovery Line had to be moved to the roof because of lack of space.	CW/HR	Supply Duct
Floating ceiling elevation was lowered to provide more service space.	Floating Ceiling	MEP components
Cable Tray was moved near the wall to provide the necessary horizontal clearance.	Cable Tray	Supply Duct
Cable Tray had to shift elevation in its layout to provide the vertical clearance.	Cable Tray	Pipes & Doors
The rain–storm water pipe run was redundant as it was discontinued at the lower floor.	RWD pipe	N/A
Location and dimensions of the slab opening was modified to provide the vertical passage of the MEP systems.	Slab Openings	Vertical Pips Stacks
The designed trim in the concrete beam was not necessary. We changed the design to cancel the trim.	Concrete Beam	N/A
Missing pipe sizes in the plumbing drawings were identified and addressed, which helped to clarify and reduce RFI's.	Pipes	(no data)
Dimension and location of the slab opening on 6th floor slab (for the electrical room) was modified, and another opening was added.	Conduits	Slab Openings
The floor drain and the related sanitary line located in Room 516 were mistakenly discontinued.	Sanitary pipe	N/A
The ventilation of acid neutralizers was added because there was no ventilation in the 2D design drawings.	Equipments	N/A
Sizes of the sanitary pipes for fume-hood and sinks: it was not designed in the schematic drawings.	Sanitary Pipes	N/A
The drawings lacked the layout of conduits in the labs. The layout of Exhaust ducts had to change in the model to avoid interference.	Conduits	Exhaust duct / diffusers
Due to the slope of the slab, the available service space had less height than assumed. Layout of the ductwork was changed.	Ducts	Sloped Roof Slab
Originally, pipes were designed to be installed above the ducts. This order and sequence was reversed.	Ducts	HW pipe & HR/CW pipe
The conduits interfere with the duct and block the diffusers. The layout of ducts and positioning of diffusers was changed.	Diffusers & Ducts	Conduits

The first column provides a brief description of the nature of the detected conflict, and the necessary changes we made in the model to resolve the identified interference. The next two columns indicate the components that where involved in the interference. In some cases where the detected conflict involved only one component, the column B is marked (N/A).

Table 2.2 provides a summary of the areas modelled in this case study and the number of issues and interferences addressed. This table also indicates the man-hours utilized in developing these snapshots. Apart from the fact that there is a learning-curve effect to develop the model, there are other factors determining the resource requirements of such a modelling task. These factor include the architectural complexity of the model, the available level of detail and completeness of the MEP-systems' design development, the complexity and congestion of components of the MEP systems, and the availability of the knowledge of experts (specialty trades, subcontractors and consultants).

Table 2.2: The results and area of the three critical spaces modelled

Critical Space Modelled	Area (m^2)	Complexity Level	Productivity Level	No. of Interferences	Time (hrs)
6th Floor Corridors	250	Medium Architectural Complexity Medium MEP Complexity	Low (starting snapshot, networking)	13	120
Main & 2nd Floor Corridors	360	High Architectural Complexity Low MEP Complexity	Medium	12	80
5th floor typical labs	200	Low Architectural Complexity High MEP Complexity	High (software upgrade, on-site interaction)	27	100

The utilized man-hours in the last column is a strategic parameter in performing 3D modelling and coordination, as this will determine the cost of employing such a process. In this case study, this parameter was influenced by the size of the target modelling space (e.g. area of critical space modelled), the complexity level of the target space to be modelled, and the productivity of the modelling process. The architectural complexity together with MEP complexity and congestion level of each snapshot is reflected in the third column of table 2.2. These factors influence the amount of work necessary for modelling a particular snapshot and therefore, the required hours to complete the coordination process. We tried to classify these factors on a low, medium and high scale. This classification was based on the variety and quantity of elements that had to be modelled, the complexity of the design layout, the congestion of components, and the completeness of the design information.

The productivity level of this modelling process is presented in the fourth column of Table 2.2, also on a scale of low, medium and high productivity rate. Several factors affected our productivity throughout this case study, including the 3D modelling software. Just before modelling the last snapshot, we had a chance to upgrade to a more recent version of ABS, which considerably enhanced the modelling productivity of MEP components. One of the most important factors improving productivity, however, was the availability of expert knowledge. During the modelling and coordination of the last snapshot, we had the most access to the specialty trades, and everyday interaction with the consultant engineers, and subcontractors. This significantly improved our productivity in producing a coordinated 3D model.

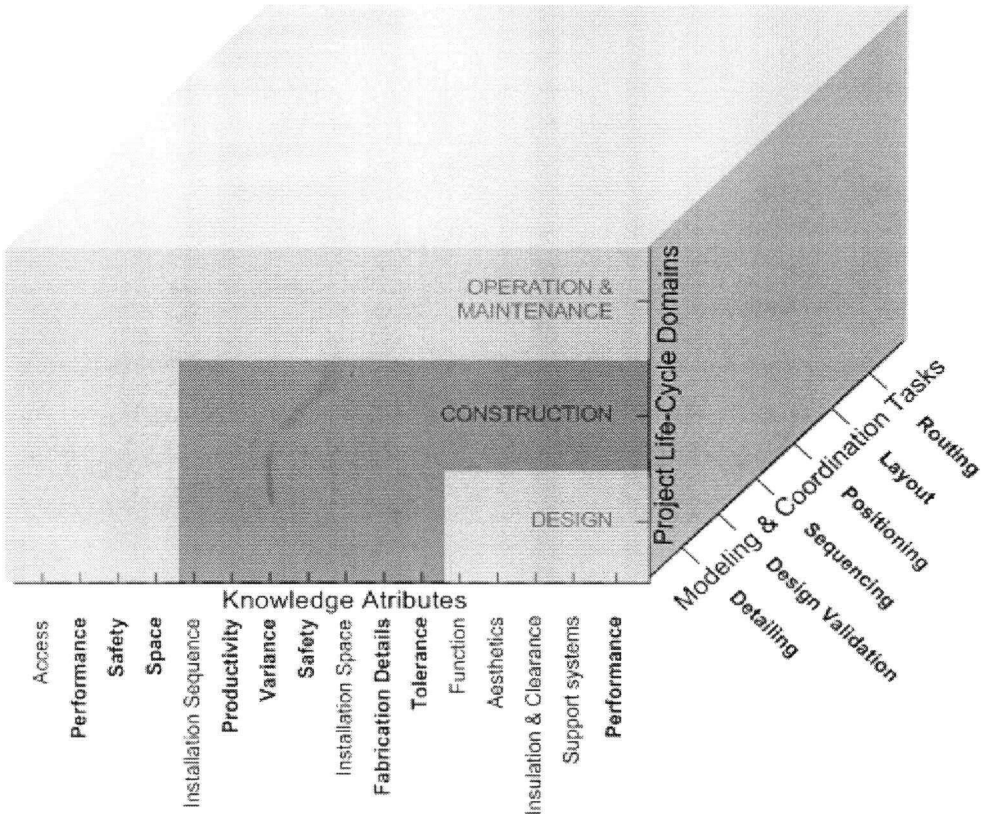
The 3D modelling and coordination process assisted all project team members in visualizing each system and its relation to others. This resulted in better communication between trades which in turn helped to unveil hidden constraints. In addition, this gives each subcontractor a warning of the critical factors, areas or elements for their system. The construction knowledge implemented in the 3D model reveals the actual availability of space and potential points of concerns and conflicts to the project team, which could not be demonstrated by the schematic details of 2D drawings. The 3D model provided an integrated view of the design perspective, together with implicit constraints of codes and specifications, and the constructability concerns of the trades and subcontractors. Although a specialty trade might be well aware of all these constraints and might have a clear picture of these critical points of concern, there are many other trades working in the same space that do not have this specialty knowledge and awareness.

2.4 CLASSIFICATION OF MEP COORDINATION KNOWLEDGE

Throughout the course of this case study, we identified the design and construction knowledge utilized to create a coordinated and constructable design. We classified this knowledge in a framework that associates the design and construction constraints that govern the modelling and coordination process with the knowledge domain, the domain context, and the specific modelling and coordination task. Our goal in developing this framework was to formalize the MEP coordination knowledge we collected in a way that conveys the context of the knowledge, represents the generality of the knowledge, enables reuse of the knowledge across multiple projects, and potentially supports computer-based implementation.

Figure 2.7 shows the three dimensions of the framework developed to represent the design and construction constraints captured from the case study, which included the knowledge domain, the specific knowledge attributes, and the modelling and coordination tasks. The documented design and construction constraints are shown in Table 2.3 and will be discussed later. This framework builds on and extends the knowledge items identified by Korman et al. (2003). To the best of our knowledge, this is the only time that their work has been applied to classify the knowledge captured actively and firsthand from an MEP coordination process on an actual project. We added some new attributes based on the facts of this case study, industry terminology, and the knowledge items used in other constructability frameworks. Note that in this case study, we were more involved with the construction experts and therefore the developed knowledge attributes relate more to the construction domain.

Figure 2.7: **The three dimensions of the framework used to classify the design and construction knowledge collected from the case study, which includes the knowledge domain, the specific knowledge attributes and the modeling and coordination tasks.**



Note: The knowledge attributes shown in bold highlight the specific extensions we made to the framework developed by Korman et al. (2003).

The bold items shown in Figure 2.7 highlight the specific knowledge attributes we added to represent the data collected from the case study. We define these new attributes as follows:

- ***Design Performance:*** The performance attribute represents the constraints, which if not met, will cause a performance issue in the component or the system. If this knowledge is formalized as design codes, we refer to it within the context of the design knowledge domain. For example, RWD pipes should maintain a 1% minimum slope (Constraint #11 in Table 2.3).

- ***Construction Tolerance:*** This attribute accounts for the difference between what is designed and what is built. For example, the corridor design might be 1800 mm wide with straight-angled walls throughout the length of the wall and with a constant width. In reality, however, the constructed corridor might have slightly different dimensions, or angles. Therefore, when designing the layout of the components in the corridor, we should maintain a buffer to account for these tolerances. For example, the ducts should maintain a minimum clearance from the adjacent walls and slabs (Constraint #1 in Table 2.3). Note that tolerance constraints represent buffers to account for contingencies and unpredictable differences in dimensions of architectural systems, whereas 'construction variance' constraints account for definite and predictable differences of dimensions of components of MEP systems.

- ***Construction Variance:*** This attribute accounts for constraints imposed as a result of the difference between design dimensions of the components of the system with the actual dimensions encountered when constructing these systems. For example, the actual diameter of a 4-inch pipe is closer to 5 inches. In another example, to construct a 4-inch pipe vertically inside a wall, which goes through the floor slab to the floor beneath, the contractors had to use a place holder which was about 6.5 inches, which required the wall thickness to be increased (Constraint #14 in Table 2.3).

- ***Construction Fabrication Details:*** These constraints reflect industry practices when fabricating parts and constructing systems. For example, the minimum radius for fabricating a round duct-fitting elbow should not be less than the diameter of its cross-section (Constraint #12 in Table 2.3).

- ***Construction Safety:*** This attribute represents the constraints that are imposed to ensure safety during construction. For example, the cable tray has to maintain a 15 cm vertical clearance zone anywhere on the top side (Constraint #19 in Table 2.3).

- ***Construction Productivity:*** There are particular constraints that if they are not met, the construction productivity would decrease. For example, if we route the pipes on top of the duct and below the ceiling, the productivity of installation would decrease drastically (Constraint #6 in Table 2.3).

- ***Operational Space:*** This attribute represents the conditions where space considerations are imposed to ensure that the systems are operational. For example, the air diffusers should maintain a minimum distance from the walls so that they can circulate the conditioned air properly in the room (Figure 2.5).

- ***Operational Safety:*** This attribute represents the constraints that are imposed to ensure safety during operations and maintenance of the system. For example, the 15 cm clearance over the cable trays ensures the *safety* zone over the cable trays during operation (Constraint #19 in Table 2.3). Should this constraint be overlooked, a possible short connection between cables and pipes could be disastrous at any point in the building life cycle.

- ***Operational Performance:*** Constraints that are required to ensure the performance of the building systems while in operation. These issues could be anywhere from reducing system efficiency to a total malfunction. Unlike design performance attributes, these constraints are not formalized in the form of design codes and requirements. They are implicit in the industry, embedded in the experience of the specialty trades. For example, U-shaped over-passing creates air traps in pressure pipes, which hinders operational performance (Constraint #7 in Table 2.3).

Figure 2.7 also shows the six modelling and coordination tasks that were executed in developing a coordinated model. We noticed that many of the constraints are valid in the context of the modelling and coordination tasks they are used for and we tried to account for that in our classification. Essentially, the modelling and coordination tasks represents "how" the constraints affect the coordination process, whereas the knowledge attributes represent "why" the constraints affect the coordination process.

Table 2.3 presents the design and construction constraints, which we identified as we modelled and coordinated the various MEP systems, in relation to the framework shown in Figure 2.7. For each building system (Column 1), we present the modelling and coordination constraints (Column 2), the knowledge domain (Column 3), the knowledge attributes (Column 4), and the specific modelling and coordination task (Column 5). The following example helps to illustrate the functionality of the framework, grounding it in a real world example.

Table 2.3: **The design and construction constraints identified in the case study, classified according to the knowledge domain, knowledge attributes, and modelling and coordination tasks.**

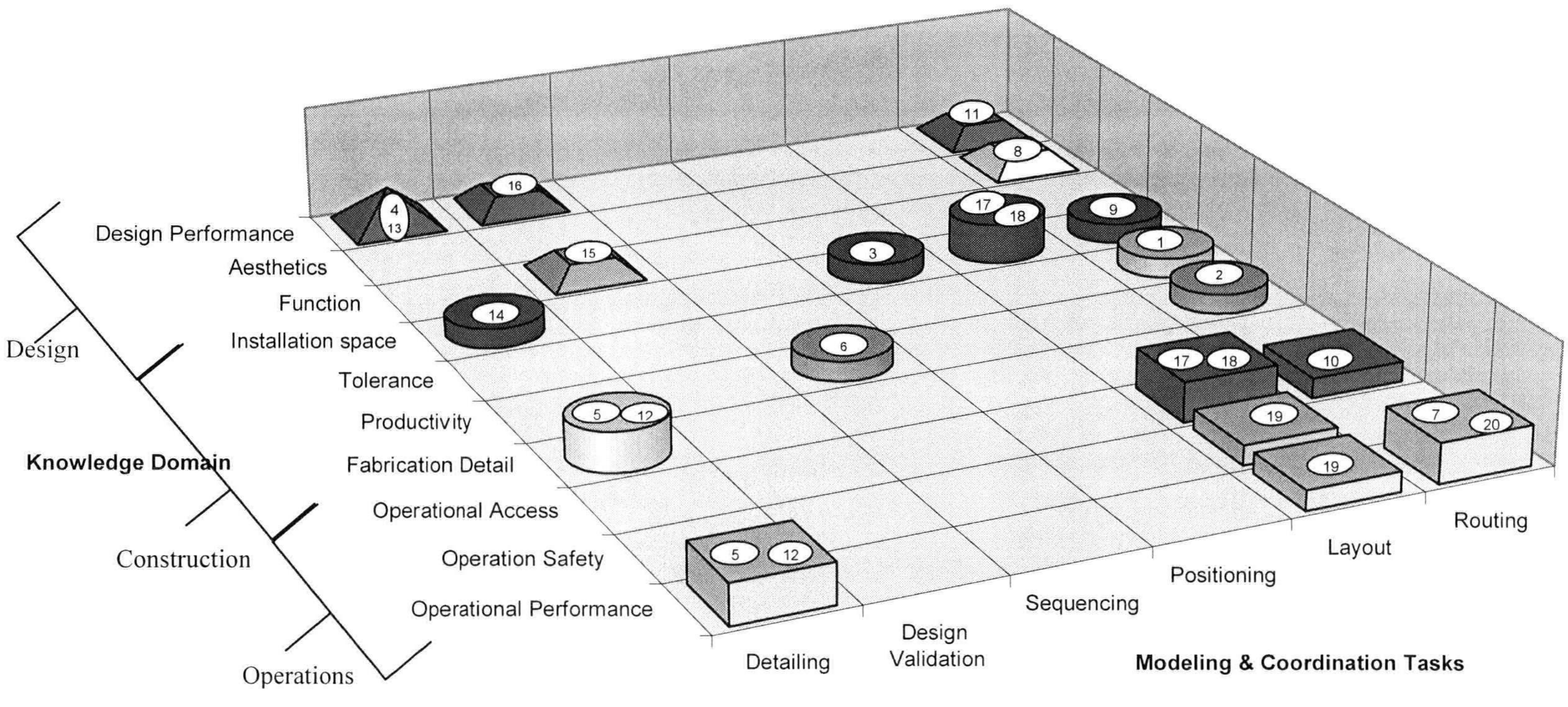
System		(2) Modeling and Coordination Constraints	(3) Knowledge Domain	(4) Knowledge Attribute	(5) Modeling & Coord Task	(6) Korman's Knowledge attribute
Mechanical	1	The ducts should maintain a minimum clearance from the adjacent walls and slabs.	Construction	Tolerances	Routing	Clearance
	2	The ducts, needing the largest supports, should be positioned closer to the slab.	Construction	Productivity		Support System
	3	In case of external insulation of equipment, positioning should account for installation space.	Construction	Installation Space	Positioning	Insulation Installation Space
	4	The code implies the thickness of the duct's external insulation or internal lining.	Design	Performance	Detailing	Insulation
	5	The minimum standard radius of a round fitting elbow can not be less than its diameter.	Operation Construction	Performance Fabrication		
	6	It is better to install the ducts first, due to their size and inflexibility.	Construction	Productivity	Sequencing	Sequence
Plumbing - Process Piping	7	U-shaped over passing creates air traps in pressure pipes; Avoid them.	Operation	Performance	Routing	
	8	The RWD line can not run bellow the false-ceiling elevation.	Design	Aesthetics		
	9	In assigning space to pipes, should account for installing insulation.	Construction	Installation Space		Insulation Installation Space
	10	Pipes should not be positioned above the ducts, due to higher maintenance frequency	Operation	Access		Access Sequence
	11	RWD pipes should maintain a 1% minimum slope.	Design	Performance		Slope
	12	The minimum standard radius of a round fitting elbow can not be less than its diameter.	Operation Construction	Performance Fabrication	Detailing	
	13	The code implies the thickness of the insulation around the pipe.	Design	Performance		Insulation
	14	The placeholder used to hold a 4" vertical stack pipe in a wall, will need at least a 7" wall	Construction	Variance		
	15	The RWD routing should connect the vertical stacks of the adjacent floors.	Design	Function	Validating Design	Function
	16	All Sanitary Drain stacks have to be connected to the vent stacks going up from that floor.	Design	Performance		System/Function
Electrical	17	The cable tray has to maintain a 60 cm horizontal clearance on one side to provide access to cables.	Operation Construction	Access Installation Space	Layout	Access Clearance
	18	The cable tray has to maintain a 30 cm vertical clearance on top side to provide future accessibility to cables.	Operation Construction	Access Installation Space		Access Clearance
	19	The cable tray has to maintain a 15 cm vertical clearance zone anywhere on top side.	Operation	Safety Performance		Clearance
	20	The number of maximum 90 degree elbows from start to finish for a conduit is four.	Operation	Performance	Routing	

We identified a soft conflict in the routing of the conduits where the spacing and curvature of the conduit had to be adjusted so that all the conduits could fit into the opening (Figure 2.6). This conflict was a result of a constraint presented by the electrical subcontractor that indicated, "The number of maximum 90 degree elbows from start to finish for a conduit is limited to four" (Constraint #19 in Table 2.3). The subcontractor explained that this code requirement is set to avoid any performance deficiency: excessive 90-degree elbows and bends could result in damaging the cables in the conduits and reduce the efficiency and functionality of the system. This constraint affects the routing of conduits, and therefore, the modelling and coordination of the electrical system. We explained that performance concerns are implicit within this constraint, and failure to meet this constraint would affect the operation life cycle of the electrical systems. Therefore, this constraint relates to the electrical system, the modelling task of routing, the operations knowledge domain, and the operational performance knowledge attribute, as shown in each of the columns in Table 2.3 for this constraint.

We also tried to correlate each constraint with the corresponding knowledge item from Korman's classification (Column 6). However, we realized that in some cases we could not identify any corresponding knowledge item, which is why certain fields are blank, indicating a need to develop additional attributes to enhance the knowledge base. In addition, in some cases the constraints corresponded to multiple knowledge items, or even multiple domains, which suggests a degree of ambiguity and subjectivity when trying to utilize Korman's framework using actual project data. The knowledge classification in this case study has provided a useful validation of Korman's framework.

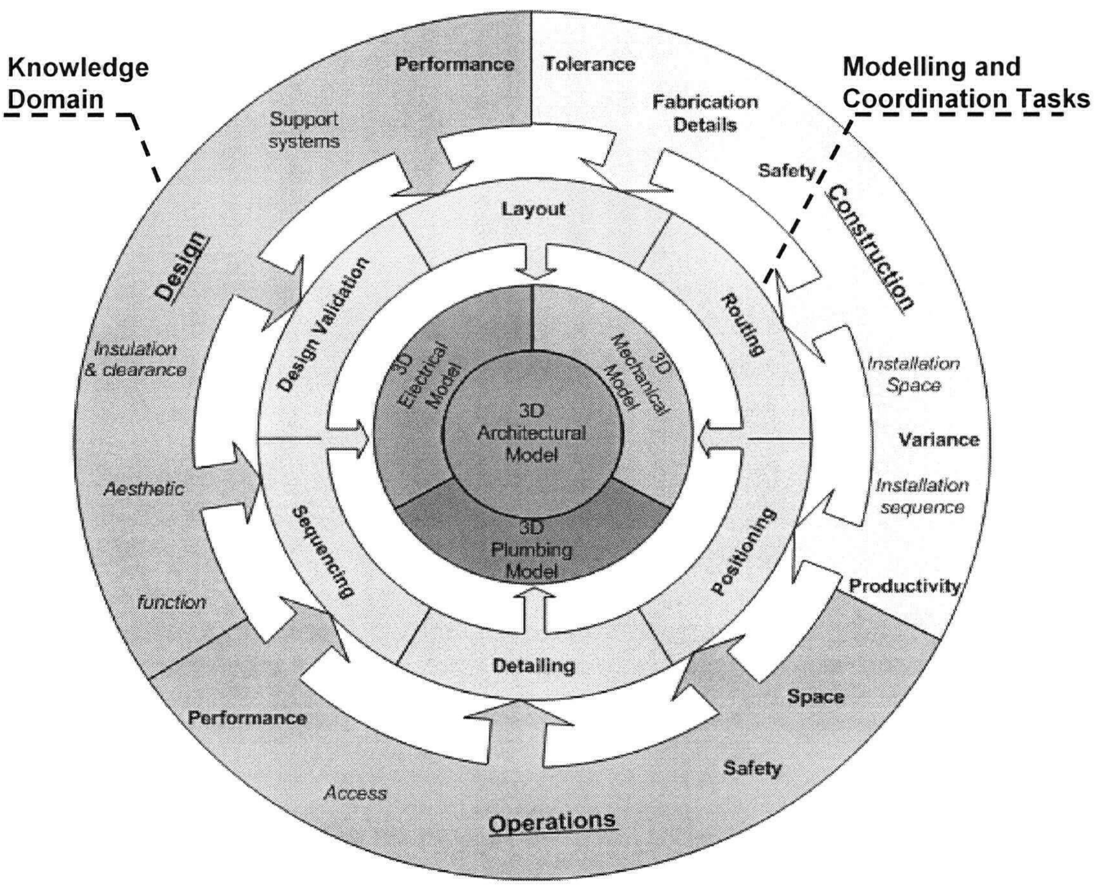
Figure 2.8 shows the distribution of the constraints across the knowledge domains and attributes in relation to the modelling and coordination tasks. The numbers on the representative data points correspond to the row numbers in Table 2.3. We can see that in this sample of collected knowledge, routing, detailing and layout are the most critical coordination tasks. It also shows that the driving attributes in this sample are "operational performance," "construction installation space," and "design performance." In addition, it indicates that most of our data originates from the construction and operations domains.

Figure 2.8: Distribution of the constraints presented in Table 2.3 across the knowledge domains and associated attributes, and in relation to the modeling and coordination tasks



A key purpose for acquiring and classifying the MEP design and coordination knowledge is to provide a framework that could be used in a computer tool to facilitate the MEP coordination process. Previously, we described the process of developing an integrated and coordinated 3D model on this project (Fig. 2.3b). Currently, the project team provides the rationale and reasoning behind the modelling and coordination decisions, which is implicit in the design process and tools. We believe this knowledge should be explicitly linked to the particular modelling and coordination tasks for each system component, enabling conflicts to be identified and resolved as the systems are being modelled. Figure 2.9 provides a graphical representation of how we think the framework could enhance the MEP coordination process. The knowledge domains and attributes (the outer ring) should inform the 3D modelling and coordination tasks (the middle ring) to create an integrated and coordinated building model (the inner circle).

Figure 2.9 Graphical representation of the MEP coordination knowledge, and how it relates to the 3D modelling and coordination process



2.5 CONCLUSIONS AND FUTURE WORK

This paper described a case study that investigated the process and impact of modelling and coordinating building systems in 3D. We documented the 3D modelling and coordination process, evaluated the software tools support of this process, documented the resources required to execute this process, and assessed the impact of the 3D models on the coordination process. Over a two-month period, we modelled three critical spaces focusing on corridors and laboratories, which totalled over 800 m^2. We identified 25 design errors, omissions, and inconsistencies, and avoided 25 MEP coordination issues and conflicts.

Our role in the 3D modelling and coordination process provided us with a unique opportunity to collect specific and detailed MEP coordination knowledge. We identified the design and construction constraints that govern the modelling and coordination process. We classified this knowledge in a framework that associates the design and construction constraints with the knowledge domain, the domain context, and the specific modelling and coordination task. We believe that understanding the knowledge behind each constraint, and the coordination tasks affected by these constraints was a key contribution of this research.

Further research is needed to extend the types of knowledge represented, to provide more structure to the design and construction constraints, and to validate the proposed framework. We identified the design and construction knowledge that was important for modelling and coordinating mechanical, electrical and plumbing building systems. To develop integrated solutions that work for all systems, it is important to also represent the knowledge that is relevant to other domains, particularly the architectural and structural design constraints. To further characterize and formalize the design and construction constraints we identified, we intend to develop a prototype knowledge-based system that will represent these constraints explicitly and formally to support real-time conflict detection as the building systems are designed and coordinated. We will use the prototype system and other case studies to extend and validate the proposed framework.

2.6 REFERENCES

Barton, P.K. (1983). *Building Services integration*, E & FN Spon, London

"Constructability: a primer." (1986). *Publication 3-1*, Construction Industry Institute, Bureau of Engineering Research, University of Texas at Austin, Texas.

"Constructability and constructability programs: White paper." (1991). *J. Constr. Engrg. Mgmt.*, ASCE, 117 (1), 67-89.

Fischer M., and Tatum, C.B., (1997). "Characteristics of Design-Relevant Constructability Knowledge." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 123 (3) 253-259.

Hanlon, E.J., and Sanvido, V.E., (1995). "Constructability Information Classification Scheme." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 121 (4) 337-345

Korman, T.M., Fischer, M., and Tatum, C.B., (2003). "Knowledge and Reasoning for MEP Coordination." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 129(6) 627-634.

Korman, T.M., and Tatum, C.B., (2001). "Development of a Knowledge-Based System to Improve Mechanical, Electrical, and Plumbing Coordination." *Technical Report No. 129,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Songer, A.D., Diekmann, J., and Al-Rasheed, K. (1998). "The Impact of 3D Visualization on Construction Planning," *Proceedings of the International Congress on Computing in Civil Engineering,* ASCE, Reston, VA.

Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration.", *Technical Report No. 122*, Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Staub-French, S., and Tabesh, A., (2005). "Case Studies of 3D/4D Modelling for Building System Coordination and Constructability Analysis." *Submitted to the ASCE Specialty Publication on Constructability.*

Tatum, C.B, (1988). "Classification system for construction technology." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 114 (3) 344-363.

Tatum, C.B., and Korman, T. M., (2000). "Coordinating Building Systems: Process and Knowledge." *J. Arch. Engrg.*, ASCE, New York, NY, 6 (4) 116-121.

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- Paul Demeule; Daryl-Evans Mechanical Ltd.

CHAPTER 3:
DISCUSSIONS AND CONCLUSIONS

This chapter describes the evaluation of the 3D modelling process and its impact on the coordination of MEP systems. Specifically, it describes the interferences identified in the MEP coordination process, the resources required to execute a 3D modelling process, the benefits of such a modelling task, and the lessons learned.

3.1 CONFLICTS AND COORDINATION ISSUES IDENTIFIED

In this project, I modelled approximately 800 m2 of laboratory and corridor space over a two-month period. I identified and resolved 25 design errors, omissions, and inconsistencies, and identified and avoided 25 MEP coordination issues and conflicts. Table 3.1 provides a summary of some of the interferences detected in this case study. The first two columns indicate the components that were involved in the interference. In some cases where the detected conflict involved only one component, the column B is marked (N/A). The third column provides a brief description of the nature of the detected conflict, and the necessary changes I made in the model to resolve the identified interference. Finally, the last column represents the modelling and coordination tasks performed, to resolve these issues.

This table is only a summary of the variety of the identified issues in the case study. The detailed summary of a complete list of the identified issues and coordinated conflicts in this case study was presented in an illustrative report as part of a presentation to the project team. (Appendix A.)

Table 3.1: **Summary of interferences detected between components and the corresponding coordination task.**

Interfering Components A	Interfering Components B	Interference detail	Coordination Task
CW/HR	Supply Duct	Chilled Water/ Heat Recovery Line had to be moved to the roof because of lack of space.	Design Validation /Detailing
Floating Ceiling	MEP components	Floating ceiling elevation was lowered to provide more service space.	Detailing
Cable Tray	Supply Duct	Cable Tray was moved near the wall to provide the necessary horizontal clearance.	Layout
Cable Tray	Pipes & Doors	Cable Tray had to shift elevations in its layout to provide the vertical clearance.	Layout
RWD pipe	N/A	The rain–storm water pipe run was redundant as it was discontinued at the lower floor.	Design Validation
Slab Openings	Vertical Pips Stacks	Location and dimensions of the slab opening was modified to provide the vertical passage of the MEP systems.	Detailing
Concrete Beam	N/A	The designed trim in the concrete beam was not necessary.	Detailing/ Design Validation
Pipes	(no data)	Missing sizes in the plumbing pipes in drawings helped to clarify and reduce RFI's.	Detailing/ Design Validation
Conduits	Slab Openings	Dimension and location of the slab opening on 6th floor slab (for the electrical room) was modified, and another required opening was added.	Detailing/ Design Validation
Sanitary pipe	N/A	The floor drain and the related sanitary line located in Room 516 were mistakenly discontinued.	Design Validation
Equipments	N/A	The ventilation of acid neutralizers – added because there was no ventilation in the 2D design drawings.	Design Validation
Sanitary Pipes	N/A	Sizes of the sanitary pipes for fume-hood and sinks: it was not designed in the schematic drawings.	Design Validation
Conduits	Exhaust duct / diffusers	Proper elevation and layout of the conduits in the labs - it was not designed.	Layout
Ducts	Sloped Roof Slab	Due to the slope of the slab, the available service space had less height than assumed.	Layout/ Positioning
Ducts	HW pipe & HR/CW pipe	Originally, pipes were designed to be installed above the ducts.	Sequencing/ Routing
Diffusers & Duct	Conduits	The conduits would interfere with the duct and block the diffusers.	Routing/ Positioning

3.2 RESOURCE REQUIREMENTS

I documented the resources required to create and coordinate the 3D models developed for this case study (see Table 2.2.). The resources required are a strategic parameter in performing 3D modelling and coordination, because it will determine the cost of employing such a process. Although there is a learning-curve effect, there are other factors that determine the resource requirements of such a modelling task: the architectural complexity of the model, the available level of detail and completeness of the MEP designs, the complexity and congestion of components, and the availability of the knowledge of experts (specialty trades, subcontractors and consultants).

Based on my experience of the three spaces modelled, I tried to estimate the number of interferences and the time required to model and coordinate the entire project in 3D. To simplify, I assumed that the expertise available and the design development are the same throughout the modelling exercise. I also neglected the learning curve on modelling productivity, and assumed a productivity equivalent to what I accomplished at the final snapshot. As a result, I considered three factors: (1) the floor area of the model, (2) the architectural complexity of the model on a scale of 1 to 5, and (3) the complexity of MEP systems based on congestion and complexity of components on a scale of 1 to 5. Based on the data I had on the snapshots, and using the following equation, I could solve this equation for three snapshots and find approximations for the coefficients of A, B and C.

[A(MEP complexity) + B*(Arch. Complexity)]* C*(Area floor/100) = Number of Interferences*

Table 3.2: Estimated hours and number of interferences potentially identified if the entire project were modelled in 3D.

Modelling Task	Area (m2)	Complexity Level On a 1 to 5 scale: Architectural	Complexity Level On a 1 to 5 scale: MEP	Comments	# of Interferences	Hours
Complete Level 6	1050	2	3	Based on current productivity and slopes	85	100
Complete Level 5	1100	1	5	Typical labs are 80% similar.	145	80
Level 4	1300	1	4	New level	135	160
Level 3	1300	2	2	New level	70	160
Level 2	1650	4	3	The corridor was already modelled	100	200
Level 1	2900	5	4	The high-head labs are complicated.	250	320
Basement	1432	3	5	The mechanical room is the main work.	190	320

Based on this exercise, and the resulting values of A, B and C (2.6, 2 and 1 respectively), I estimated the number of possible interferences on the whole project, which is shown in (Table 3.3.) I estimate that modelling the entire project would take approximately 1,340 man-hours and that this 3D modelling effort would help to identify 975 potential interferences.

I should note that many of the issues faced in one area and floor level would reappear on other floors. In other words, a number of issues and interferences claimed above are repetitious from floor to floor. In addition, many conflicts and interferences are avoided during the modelling process, so the final "detected" interferences are actually less than what I would have faced otherwise. Further study is required to account for such double counting, to come up with a better estimate of the number of potential interferences.

3.3 Benefits of 3D MEP Modelling And Coordination

3.3.1 Visualization

The 3D modelling and coordination process assisted all project team members in visualizing each system and their relation to others. This resulted in better communication between trades which in turn helped to unveil hidden constraints. In addition, this gave each subcontractor a warning of the critical factors, areas or elements for their system. The construction knowledge implemented in the 3D model reveals the actual availability of space and potential points of concerns and conflicts to the project team, which could not be demonstrated by the schematic details of 2D drawings.

3.3.2 Integration

The 3D model provided an integrated view of the design perspective, together with implicit constraints of codes and specifications, and the constructability concerns of the trades and subcontractors. Although a specialty trade might be well aware of all these constraints and might have a clear picture of these critical points of concern, there are many other trades working in the same space that do not have this specialty knowledge and awareness. The 3D modelling process, integrated the different design data and assumptions made by individual designers, specialties and consultants in a single environment. This integration will validate the design, expose any missing data and information, and reveal any contradiction or conflict in the design.

3.3.3 Interference Detection

Recent 3D modelling software tools have the ability to identify every physical interference in the modelled systems. In addition, the visualization capabilities enable the specialty trades, designers, and coordinators to review and detect the non-physical interferences faster, better, and more accurately. When identifying possible solutions, I can instantly make the necessary changes in the systems, and trace the effect of the suggested solutions on other components and systems. Finally, when the model is coordinated and finalized, it is easier and faster to create the sections, elevations, and other necessary documentation of the systems.

3.4 LESSONS LEARNED

On this project, I created detailed 3D CAD models of multiple building systems in order to facilitate the design coordination process. In effect, I learned many valuable lessons about the 3D modelling process and the issues associated with implementing a 3D process in real-time during the design and construction of an actual project.

- To create a 3D model effectively and accurately, the 3D model should be created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction.
- A formal process must be in place for addressing the conflicts and issues identified in the 3D MEP coordination process. On this project, I categorized each issue according to the party that was responsible for its resolution. If the issue was the responsibility of the designer or consultant, an RFI was issued and the drawings were revised accordingly. However, if the issue was the responsibility of the MEP subcontractor, the MEP subcontractor was made aware

of the issue but there was no formal process for ensuring that the issue was addressed.

- Most of the professionals involved, from the designers and consultants to the subcontractors and trades and foremen, are used to communicating and understanding a 2D presentation of the design. To facilitate acceptance and understanding of the 3D models, project teams should provide both 2D and 3D representations when adopting this type of process.
- Issues and conflicts identified in an MEP coordination meeting must be documented in a way that facilitates ease of use and interpretation. The 3D model alone does not provide this type of documentation. There needs to be a complementary document that provides the necessary annotations and labeling to convey the issues identified and their resolution.
- This method of conflict resolution enables the project team to trace the effect of changes made, and its interaction with other components and systems. In addition, once the changes are finalized and issues are resolved, it is easier to create sections, elevations and other documents to communicate or record these issues and changes.
- The project specification and codes of practice were a rich source of documented knowledge. However, the challenge was to locate the right knowledge between numerous pages of information. It takes an expert in the subject to have a thorough understanding of these important details.
- 3D Modeling and MEP coordination refines and integrates project information, and reduces the number of Requests for Information (RFI) and Change Orders in the project.
- In the current practice, many of the identified issues in this research are resolved on site by the specialty trades. This is usually done under pressure of a tight schedule, and therefore, the resulting solutions are not always the best solutions. In addition, in a number of these situations, the knowledge utilized remains implicit and is not documented. By revealing and exposing the issues sooner in

the modeling process, the project team will have more time to resolve it and develop better solutions. This will result in less ad-hoc solutions and rework in the project. Moreover, by documenting the issue, the designers can prevent facing the same problem in the future.

3.5 CONCLUSIONS

This thesis described a case study that investigated the application of 3D modelling for building system coordination. I worked closely with the project team and created detailed 3D models of several critical spaces to facilitate building system coordination. I documented the 3D modelling process, documented the resources required, studied the impact of the 3D models on the MEP coordination process, and identified and classified the constraints that governed this process. The case study demonstrated that 3D technologies facilitate the development of constructable designs. Specifically, current 3D CAD technologies help project teams to identify design conflicts, design errors, sequencing constraints, productivity impacts, access issues, installation paths, fabrication details, and procurement constraints that impact the constructability of a facility design.

It will take time and effort to incorporate these technologies, particularly given the pressures and time constraints faced by construction professionals, but the evidence is mounting that the benefits far outweigh the costs. Visualization technologies, such as 3D CAD, help designers and builders to identify and resolve conflicts in the computer instead of in the field where it is time-consuming and costly.

Current 3D modelling technologies, such as ABS, enable researchers to be actively involved in a MEP coordination process and capture the knowledge first-hand, and not only based on observations of coordination meetings. This case-study is an example of such an attempt to gain a better understanding of the nature of MEP coordination, and the constraints governing this process. This understanding will help to improve the recent research contributions and can hopefully result in a more thorough framework to capture and represent the MEP-coordination knowledge.

3.6 RECOMMENDATIONS ON FUTURE RESEARCH

Research efforts should continue focus on the development of knowledge-based systems to assist the MEP coordination process. This requires the development of proper classification systems and knowledge frameworks. The ideal framework needs to be effective in capturing the knowledge and retrieving the knowledge to be used in a reasoning system.

Further research is needed to extend the types of knowledge represented in order to provide more structure to the design and construction constraints, and to validate the proposed framework. Developing a prototype knowledge-based system that will represent the design and construction constraints identified, will further characterize these constraints explicitly and formally, to support real-time conflict detection as the building systems are designed and coordinated. This prototype system, in conjunction with other case studies can be used to extend validate the proposed framework.

Implementing a 3D modelling process requires changes in the way project teams work and collaborate. Owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to capitalize on the benefits offered by these technologies. In addition, the responsibility for accuracy of the information in the model and the resulting outcomes of the project is a dilemma. More research is required to identify the organizational and legal challenges, and possible solutions for adopting the 3D modelling and coordination process in the construction projects.

Moreover, project teams modelling in 3D require increased design and coordination time. Although the additional time, and other expenses of 3D modelling coordination are offset by benefits in construction, currently those benefits are implicit and distributed between different parties involved in the project. This will affect the level of desire and motivation of the industry to evolve promptly and adopt the new coordination process. Further studies are required to address how current procurement systems in the projects, can impartially match these costs and benefits of 3D modelling and coordination for different parties involved in the project.

THESIS BIBLIOGRAPHY

Barton, P.K. (1983). *Building Services integration*, E & FN Spon, London

"Constructability: a primer." (1986). *Publication 3-1*, Construction Industry Institute, Bureau of Engineering Research, University of Texas at Austin, Texas.

"Constructability and constructability programs: White paper." (1991). *J. Constr. Engrg. Mgmt.*, ASCE, 117 (1), 67-89.

Euler, J.K., (1994). "Advantages of using 3D CAD plant models on the Construction site." *Microcomputers in Civil Engineering*, 9 (6) 435-444

Fischer, M. (1991). "Constructability input to preliminary design of reinforced concrete structures.", *Technical Report No. 64,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Fischer M., and Tatum, C.B., (1997). "Characteristics of Design-Relevant Constructability Knowledge." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 123 (3) 253-259.

Ganah, A., Anumba, C.J., and Bouchlaghem, N.M., (2001). "A survey of visualization tools to communicate buildability information." *COBRA 2001 conference*, Glascow, 2-4 September, pp.721-731 (available at www.rics-foundation.org)

Hanlon, E.J., and Sanvido, V.E., (1995). "Constructability Information Classification Scheme." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 121 (4) 337-345

Korman, T.M., and Tatum, C.B., (2001). "Development of a Knowledge-Based System to Improve Mechanical, Electrical, and Plumbing Coordination." *Technical Report No. 129,* Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Korman, T.M., Fischer, M., and Tatum, C.B., (2003). "Knowledge and Reasoning for MEP Coordination." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 129(6) 627-634.

Mahoney, J., Tatum, C. B., and Kishi, K. (1990). ''Construction site applications of CAD.'' *Tech. Rep. 36*, Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

Songer, A.D., Diekmann, J., and Al-Rasheed, K. (1998). "The Impact of 3D Visualization on Construction Planning," *Proceedings of the International Congress on Computing in Civil Engineering,* ASCE, Reston, VA.

Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration.", *Technical Report No. 122*, Ctr. for Integrated Fac. Engrg., Stanford University, Stanford, CA.

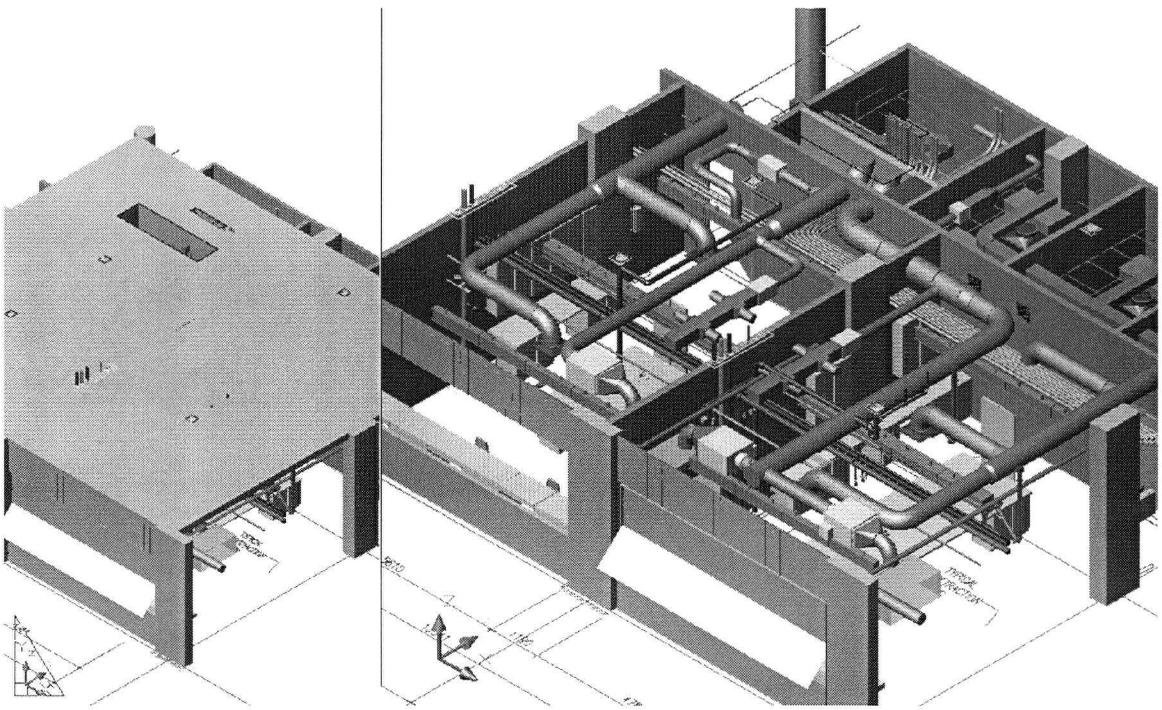
Staub-French, S., and Tabesh, A., (2005). "Case Studies of 3D/4D Modelling for Building System Coordination and Constructability Analysis." *Submitted to the ASCE Specialty Publication on Constructability.*

Tatum, C.B, (1988). "Classification system for construction technology." *J. Constr. Engrg. And Mgmt.*, ASCE, New York, NY, 114 (3) 344-363.

Tatum, C.B., and Korman, T. M., (2000). "Coordinating Building Systems: Process and Knowledge." *J. Arch. Engrg.*, ASCE, New York, NY, 6 (4) 116-121.

APPENDIX

UBC Chem-Bio Project
3D Modelling Exercise



Spring 2004

Summary of 3D Elements and Systems Modelled in this Project:

- **Architectural Systems (Pages 5-10)**

- Structural elements: round concrete columns, rectangular concrete columns, rectangular concrete beams, concrete walls, steal I-beams, Steal W –beams.
- Design elements: Walls, Wall Openings, doors, windows, roof slabs, floor slabs, Slab Openings, Slab slope, ceiling spaces, ceiling grids, curtain walls.
- Interior elements: millwork, extension arms, and appliances (sinks, fume hood, etc.)

- **Mechanical Systems (Pages 11-15)**

- HVAC system: Supply ducts and fittings, exhaust ducts and fittings, rectangular and round ducts, transitions, offsets, elbows, tees, etc.
- Air terminals: diffusers, grills
- Mechanical Piping: hot water supply and return, chilled water/heat recovery supply and return, Steam and Condensed piping.
- Equipments: Air Valves, coils

- **Plumbing Systems (Pages 16-21)**

- Sanitary Waste system and Sanitary Vent
- Rain-Storm water system
- Domestic cold water system
- Hot water /Heat Temperature Maintenance
- Emergency Shower/eyewash
- Natural Gas system
- Compressed Air and Lubricated Compressed Air systems
- Fume-Hood cold water
- Fire Protection

- **Electrical Systems (Pages 22-25)**

- Cable Tray
- Conduits
- Lighting system
- Electrical Panels

Summery of Issues and Conflicts Resolved:

1. **Design/Consultant related Issues:** These are the types of issues raised and addressed, which does concern the consultant body and most probably requires formal RFI and in some cases, changes in the drawings and/or designs. [The number in the brackets indicates the page number describing the issue]

   1.1. <u>5th Floor Typical Lab</u>

   1.1.1. Slab opening on 6th floor slab, right in the Electrical Room and the 5th floor slab extra opening. [24]
   1.1.2. The floor drain and the related sanitary line located in Room 516. [18]
   1.1.3. Missing size on the exhaust duct in 508 Lab. [12]
   1.1.4. The change in the Room 512 riser and layout of the wall. [12,13]
   1.1.5. The resulting changes in Room 512 regarding the sink CA and gas pipe. [17]
   1.1.6. Sanitary line and stack in Room 508. [18, 21]
   1.1.7. The cup sinks and their sanitary drains. [21]
   1.1.8. The ventilation of acid neutralizers (there is no ventilation).
   1.1.9. Sizes of the Sanitary Pipes for fume-hood and sinks. [18]
   1.1.10. Branching at either sides of the wall, or one side [18]
   1.1.11. Opening in the concrete block wall adjacent to riser, to pass the conduits [22,23,24]
   1.1.12. The location of the diffuser in the 518 lab [27]

   1.2. <u>6th Floor Corridor:</u>

   1.2.1. Chilled Water/ Heat Recovery line. [34,35]
   1.2.2. Floating ceiling elevation on the bridge. [34,35]
   1.2.3. Cable tray clearance and layout. [36]
   1.2.4. Finished floor heights and the sloping roof slab. [34]
   1.2.5. Arrangement of lighting fixtures. [36]
   1.2.6. The exact positioning of roof drains on the roof. [37]
   1.2.7. The layout of storm-water drain pipe and stack. [37,38]

   1.3. <u>Main and 2nd Floors Corridor:</u>

   1.3.1. The rain–storm water run discontinued at the lower floor. [39,40]
   1.3.2. The cable tray size and layout in the main floor. [40]
   1.3.3. Slab opening dimensions and trimming the concrete beam. [43]
   1.3.4. The cable tray clearance in the corridor of High-head Lab. [43,44]
   1.3.5. The difference in elevation between architectural and structural drawings. [43,44]
   1.3.6. Missing sizes in the plumbing pipes. [44]

2. **MEP Coordination-Related issues/lessons learned:** These are the issues that were raised and addressed that are of concern to the MEP trades and should serve as a

warning to avoid future conflicts. Obviously all of the previous section should also be considered by the MEP trades, in addition to the following:

2.1. 5th Floor Typical Lab

- 2.1.1. The elevation of Main Supply Ducts and their connection to the diffusers. [11]
- 2.1.2. The location of the Exhaust Duct in the Room 508, mounted at 2100 AFF. [13,14]
- 2.1.3. The positioning and layout of the Supply Duct and the Fume Hood Air Valves in Room 518. [14]
- 2.1.4. The elevation of the Return/Exhaust Duct running parallel to the windows in the labs. [14]
- 2.1.5. The interference of the wall unit, and the Vent Stack in Room 508. [9,10]
- 2.1.6. The elevation of exhaust ducts in 508 and 518 labs. [15]
- 2.1.7. The order and offset dimension of pipes to leave the proper sleeves. [16,17]
- 2.1.8. Compressed Air pipe running from Rooms 508 to 514. [31]
- 2.1.9. Relative elevation of vent pipe from 512 to 508, & duct work in 508 and 514. [30]
- 2.1.10. 6th floor, floor drains in Room 508. [18]
- 2.1.11. Compressed Air and Gas pipe to supply fume-hoods. [19,20]
- 2.1.12. Proper elevation and layout of the conduits. [22-24]
- 2.1.13. 5 degree turn in the conduit ending in the opening. [24]
- 2.1.14. Elevation of the Gas pipe in Room 518 (avoid conduits). [23]
- 2.1.15. The layout of the supply diffusers. [26,27]
- 2.1.16. Supply duct layout in Room 512. [27]
- 2.1.17. Relative elevation of sanitary waste pipe and ducts in the lab 518. [28,29]
- 2.1.18. Layout, positioning and elevation of sanitary waist in 508. [32]

2.2. 6th Floor:

- 2.2.1. The arrangement & relative elevation of HWS & R in the corridor and bridge.[34]
- 2.2.2. The proper layout and elevation for the other plumbing systems (Storm-Rain water, Domestic/Hot water systems). [36,38]
- 2.2.3. The positioning & routing of the ducts relative to the corridor walls and slab. [37]
- 2.2.4. The finished height in the labs and the service space less than indicated. [10]

2.3. Main and 2nd Floor

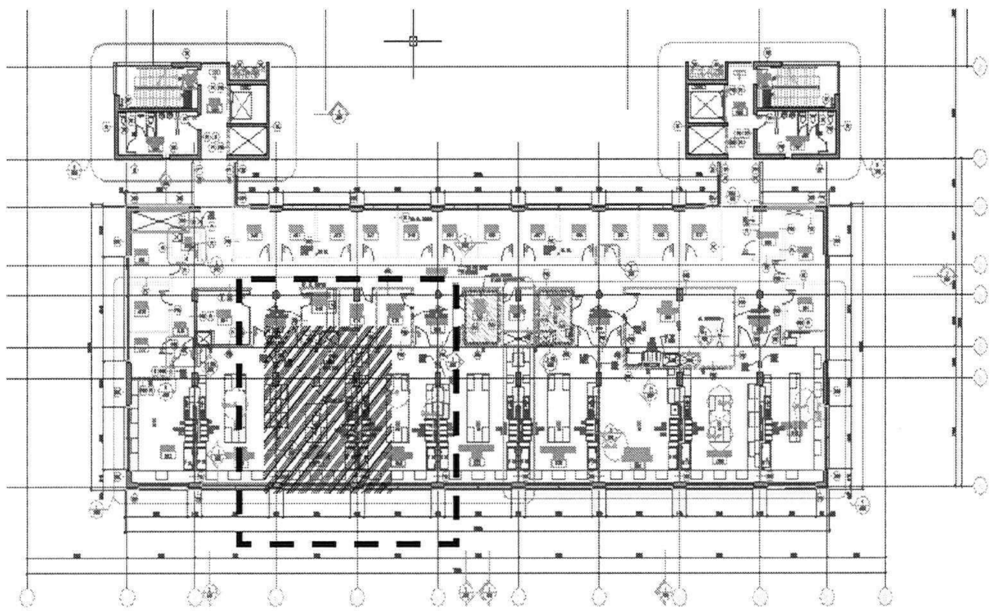
- 2.3.1. Paying attention to plumbing layout and elevation, since there are 4 different ceiling height elevations involved. [40]
- 2.3.2. Positioning in the tight area in front of the elevator (works, but there is no room for mistakes). [42-44]
- 2.3.3. Duct transitions, offsets, and elbows to maximize the usage of the space. [42,43]

3. **Unresolved Issues:** This section considers issues that either was addressed during the modelling but was not resolved, or it was only discussed and in my idea, needs further notice and careful attention.

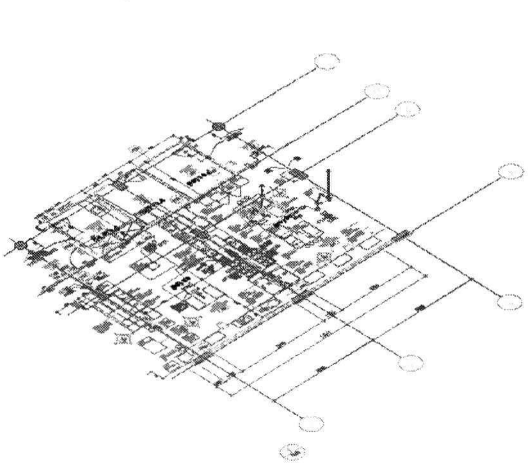
   3.1. Fire Protection in the staircase (all floors).
   3.2. Fire Protection in the corridor (Double Sprinklers) (2^{nd} floor).
   3.3. Interference of the Conduits and the Wall-mounted fire protection pipes in 2^{nd} floor.
   3.4. The thickness of the wall containing the Rain/Storm stack in 6^{th} floor. [37,38]
   3.5. The Location of diffuser in Rooms 512 and 518. [27]
   3.6. In the fifth floor, Vent line and stack near grid line 5 does not carry any size. [18]
   3.7. The effect of the sloping roof slab in the 6^{th} floor, on the service area in the labs. [10]

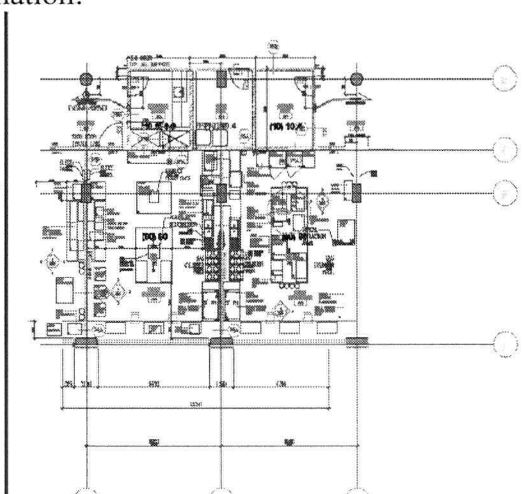
5th Floor Typical Lab

On May 20th, in a meeting with Paul (Project coordinator), Martin (From Bridge, the electrical sub) and Gary (from IMEC, the mechanical/plumbing sub) in the site office, it was decided that the next and the last snapshot to be modelled in the Chem-Bio Building should be the "Waste Treatment B" Lab on the 5th Floor [room 508]. This was in line with the general guidelines of the architect (Mike) that the next spot should be a typical lab. In addition, Martin, the electrical sub representative, was interested in the details of how all the conduits and cables could go and pass to the riser between this lab and the next room, on the north side ([room 512] Anaerobic Preparation) after which they all go vertically to the electrical room on the 6th floor.



The first few steps involved isolating the 2D drawing for the lab area, integrating all the different information and drawings available for that area, and then adjusting the grades. The following shows the architectural information:

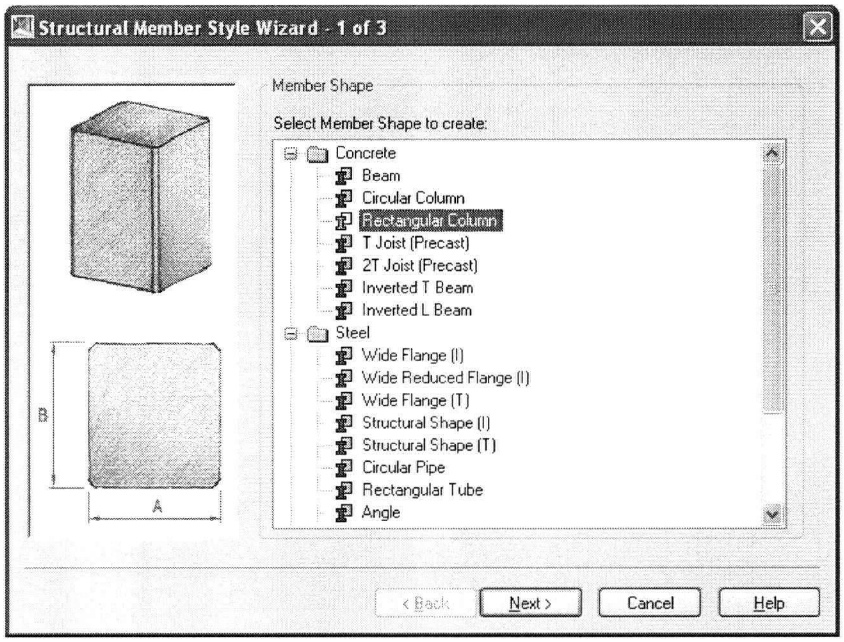




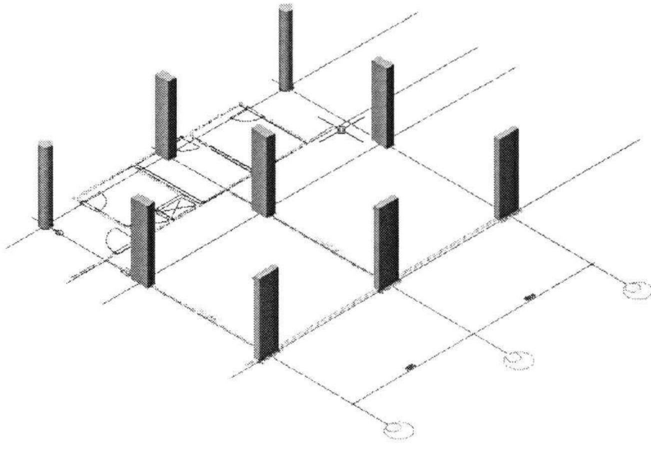
Architectural and Structural Elements

3D Structural Elements

The next step was modelling the structural elements on top of the 2D drawing. Note that for each of these elements it was necessary to define the styles of every component. Therefore, before each step, I studied the drawings and specs to acquire the necessary information and then define the particular styles and representations.



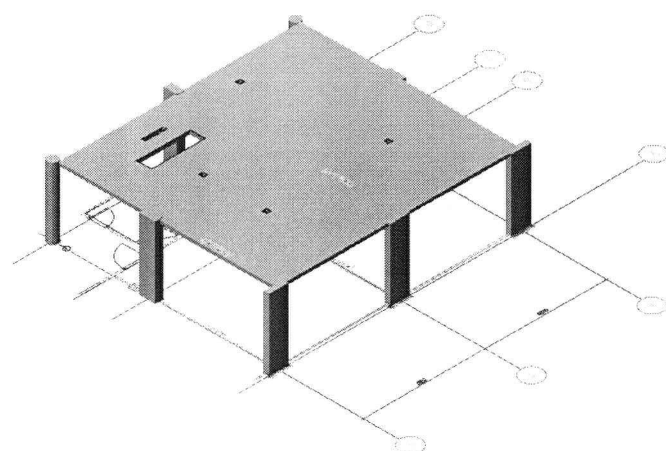
In building the Structural elements, I could not find the typical column style on the relative schedule. It turned out that those columns only show up in the 4th floor, where the previous floor columns end, and these new ones are constructed on the body of the main beam. There were three different column sizes in this area, therefore 3 different concrete column styles needed to be created and defined. (Concrete column sizes are not free format; by free format, I mean that you can assign your desired thickness to any style, unlike columns, where each style has specific dimensions).



3D Top Floor Slab

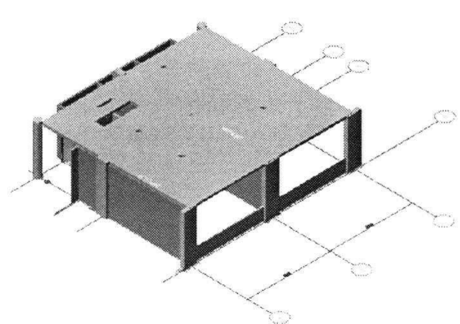
The work continued by adding the top floor slab to the model. It is a 200 MM concrete slab, with no variation on thickness, up to the edge of the column at axis 4-D (where it changes to 300MM, which is out of the scope of this model. However, the effect of extra thickness should be noted when considering the elevation of ducts and pipes running out and into that area). The slab is a free format when it comes to its thickness and slope therefore there is no need to define a style beforehand.

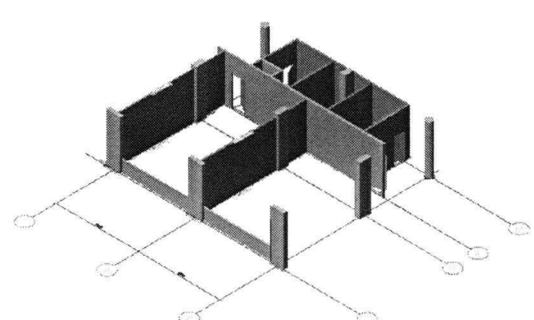
Then the openings and penetration areas were placed on the slab (as shown in the picture below). There were 4 floor drain openings and one 3000x800 opening shown on all drawings. However, another 1200x300 opening was only indicated in the "slab edge" drawings (drawing A126) but in the floor plans, it would open right in the middle of the electrical room. When I questioned the electrical sub, they mentioned that a piece of equipment would be installed right on top of that opening and the cables running from the level below to that piece. However, the exact location of it had to modified (from what shown on the slab edge drawings).



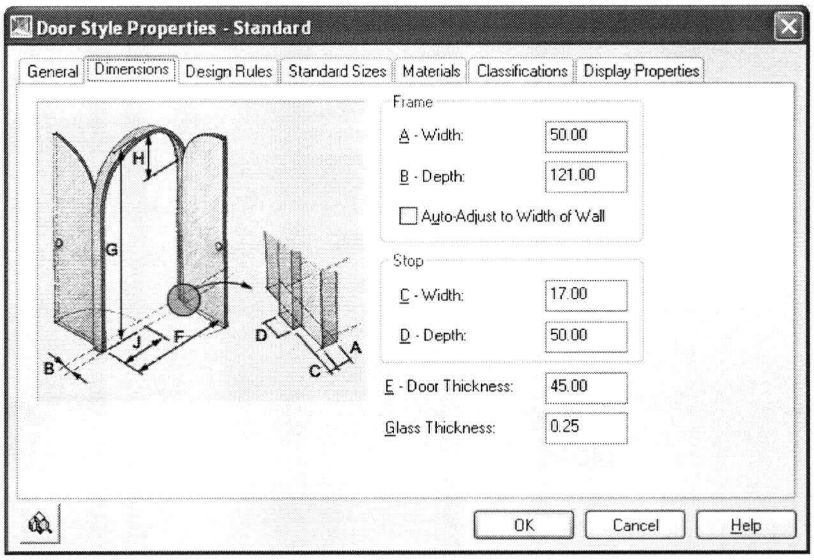
3D Walls and Doors

The next step was adding walls and doors and opening in the walls. For this snapshot, for all walls except on grid A, we have a 140MM wide concrete-block wall. For the grid line A, we just have a stud wall below the level of the windows. There were two different styles defined and used, based on the material component of them. The thickness and base height of the wall can be assigned to individual walls.





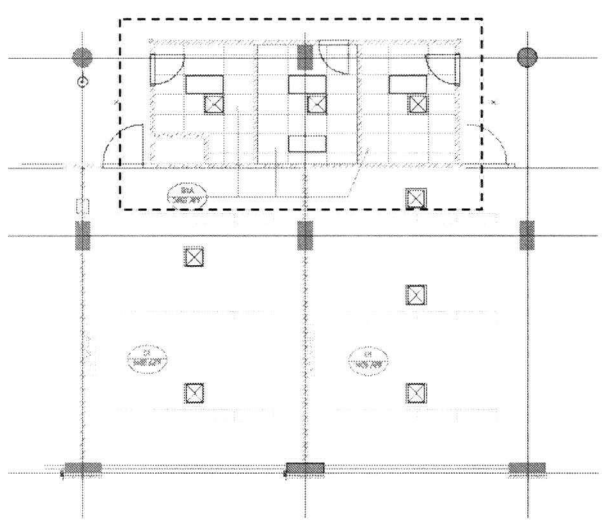
The style of the doors was modified to define the correct format for the frames and stoppers, as well as the depth of the frame and thickness of the wall. Then for five different doors, the designated width and heights were assigned.



Note that using the "design rules" tab, we can define other types of door, like a double, un-even, sliding, revolving, etc.

3D Ceiling "Spaces" and "Grids"

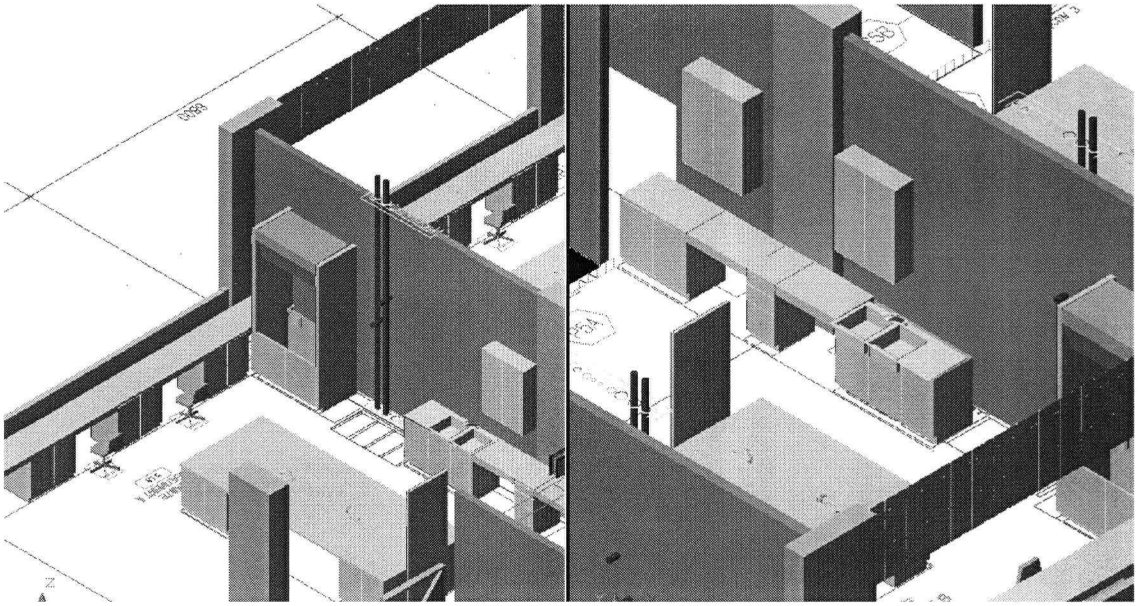
To represent the reflected ceiling layout of the- area based on the 2D platform- a combination of "ceiling space" elements and "ceiling grids" are defined, modified, and set in place. The "ceiling space" object is representing the physical dimensions and specially, the thickness of the ceiling. The ceiling grid is representing the pattern and layout of the ceiling elements, as well as, location of removable parts, lighting fixtures, diffusers, etc., which will be placed on the ceiling. The next image is highlighting the ceiling grids. The ceiling space objects can only be shown in the 3D view, and is not presented here.



Note that the Lab area has an exposed ceiling. However, the A900 series drawing (generic Research Lab Elevation and Sections) indicates that the maximum service zone is 950mm below the slab (which would be the top of the suspended light fixtures and the bottom level of the diffusers.

<u>3D Millwork</u>

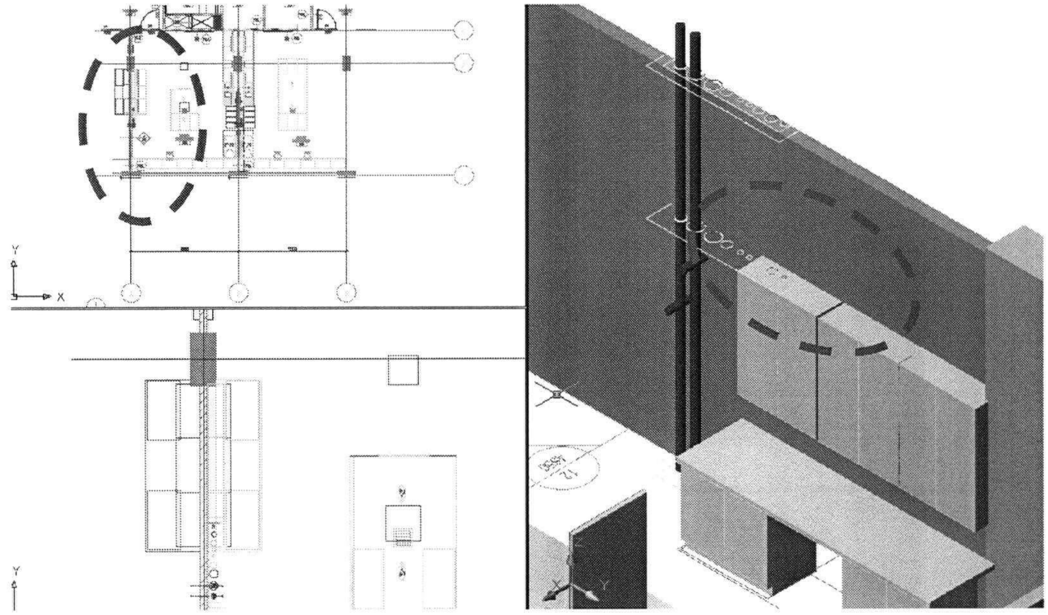
I initiated laying out the millwork in the labs, to get a better sense of "what goes where" in the lab. I used the modules available, and considered the available information in the A900 series drawings.



Note that during the modelling, we realized that we would possibly have a conflict between the vertical plumbing pipes and the wall mounted shelf units in the lab 508.

I assumed in order to avoid this interference, we should either omit one of the three shelves designed for the same place, or relocate them. However, once the plumbing layout was implemented the only pipe that would interfere in that area was a vent stack rising from the 4th floor. This issue has to be considered and coordinated between the architect and the consultants.

This **possible interference** is illustrated in the next image.



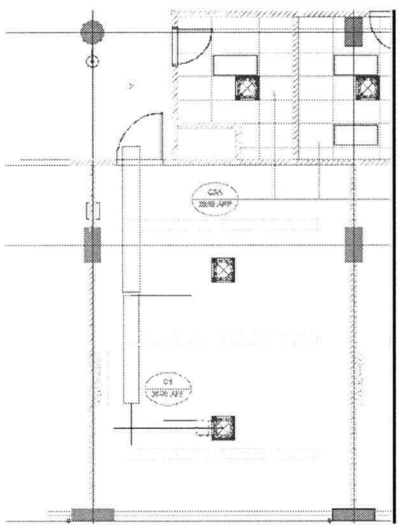
Impact of the Sloping Roof Slab on the 6th Floor available height

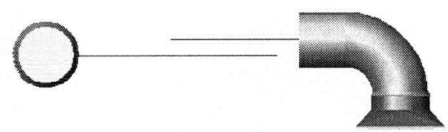
Note related to 6th floor: One of the significant contributions of this part of the modelling was detecting the effect of the sloping roof slab, on the layouts of our MEP systems. One of the issues which was not highlighted before and should be considered, is that the labs around the corridor in the 6th floor, will have a lower finished height than what indicated in the drawings, especially at the entrances to the labs where our ducts have the largest cross section. The sloping roof slab in the 6th floor will cause the labs to have about 185 mm less height than expected (nearly 3490 AFF). To add to the issue, the BOT duct elevation at the entrance of our typical lab at this level would be close to 3000 AFF. That all means that providing a 950mm service space might not be that easy.

Mechanical Elements

3D Diffusers

It is important to know the depth of the diffusers to coordinate the elevation of it. The current assumed terminal has a depth of 233 mm and it is located at 2900 AFF. Considering the necessary minimum radius of 1D when using round elbows, the 375mm duct centre line will be located at 2900+233+375 = 3508 AFF. Furthermore, the 400mm duct is routing out of a 1000x500 duct that is running under the 300 mm slab, which will locate its centre line at 4000-300-0.5*(500+100)=3400. Based on these calculations, and as indicated in the next picture, we need to modify some of our design assumptions, in order to match these two elevations.



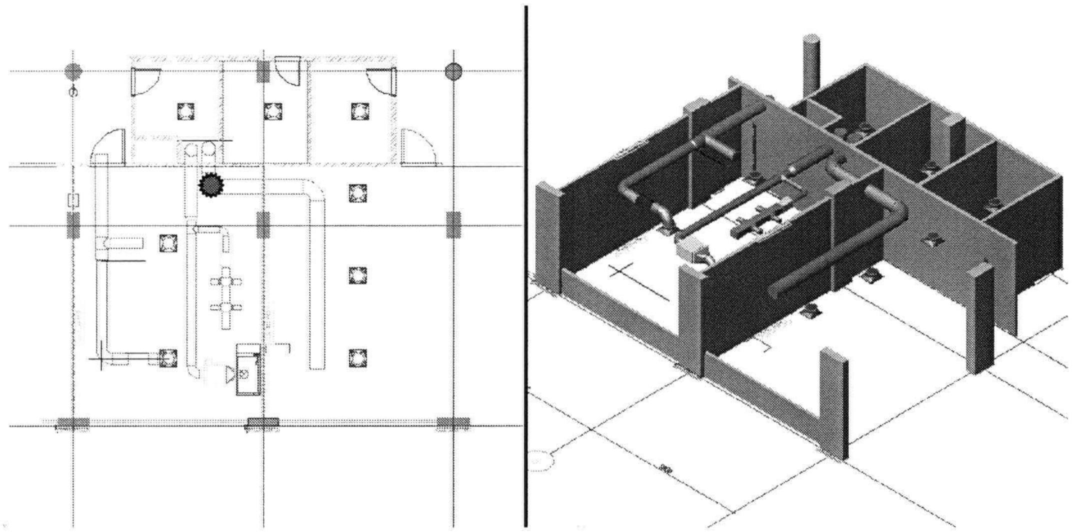


Discussing the matter later on with the Mechanical sub, he mentioned that they could use a diffuser with a depth of 3 inches (75mm) and therefore solve the problem. We only needed about a 100 mm to take care of the issue, and this change would provide about 160mm of available height.

3D Supply and Exhaust Ducts

In the next step, the supply ducts and exhaust ducts were added to the layout. In adding the exhaust ducts, the elevation constraint of the Room 512 ceiling level should be met. This means that the round ducts should run at an elevation, to clear the 2850+50 AFF.

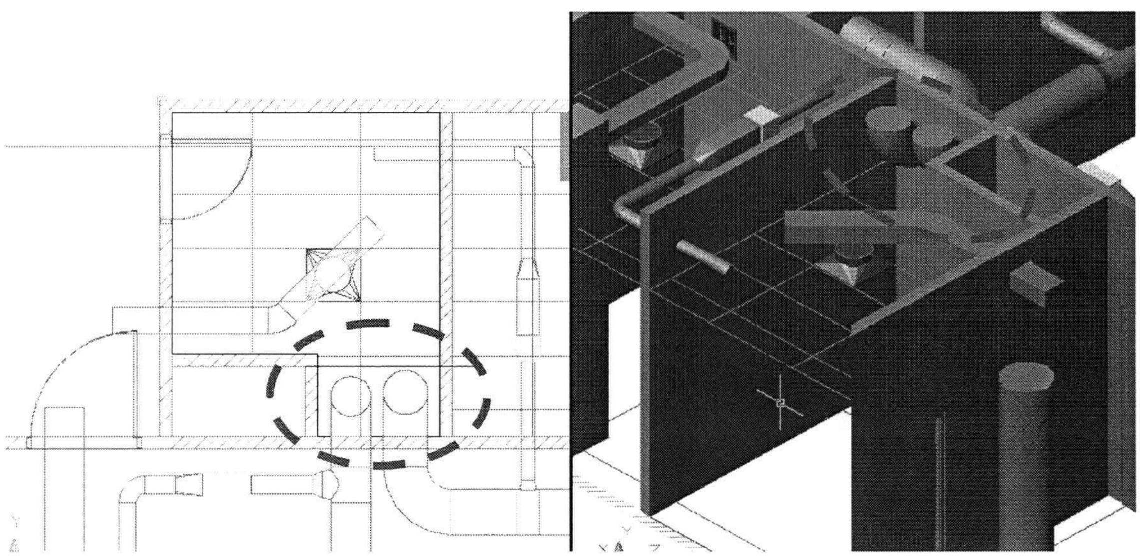
The software lacks the exhaust VAV units, and as a result, I had to use a mix of other objects to represent them. In addition, the system does not have a cross-transition of rectangular-to-round duct fitting. Therefore, a rectangular cross fitting is used with two simple transitions to represent this in element in the model.



While working on the exhaust ducts, I realized that there is a branch connected to AV-5204 which has no size indicated on the drawings (marked with the star). I assumed a 200mm round duct as the design, and the contractor representative (Gary) confirmed.

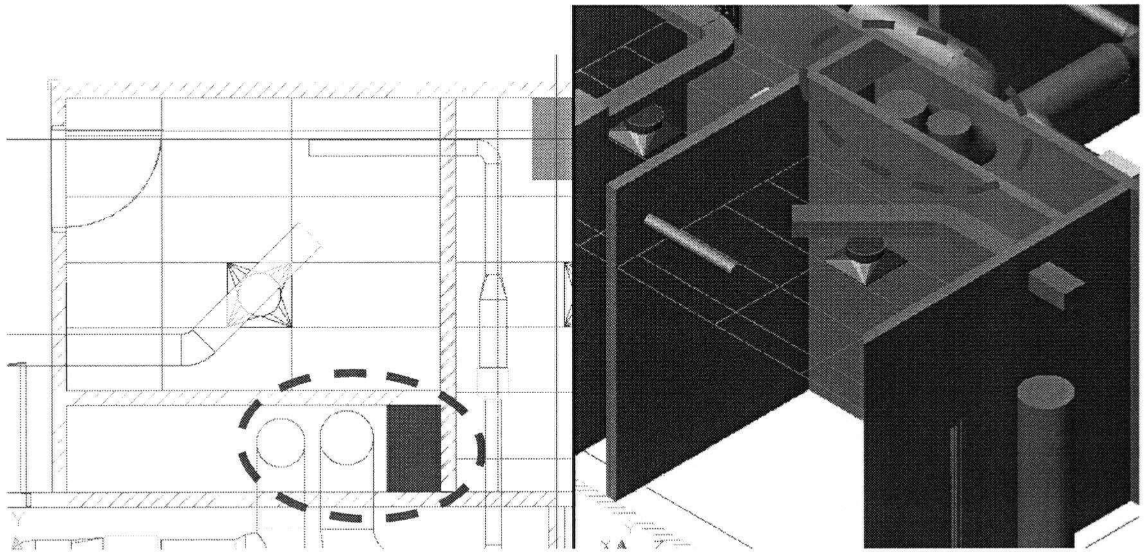
Incorporate Change in the 6th Floor Slab due to Electrical Room Layout Change:

While discussing the riser below the electrical room, Martin (from electrical sub) mentioned that the layout on the room below electrical room in the 5th floor, has changed. The next image is presenting this room and the risers in it before this change, and the one after it represents the updated design of this room with the changes implemented. Note the difference in the riser containing the two exhaust ducts.



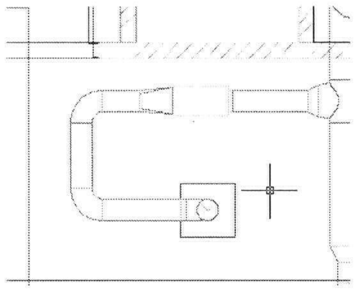
The east wall of that room has shifted 500 mm towards east, and the opening is now bigger.

Martin confirmed that he has a memo from the architect saying that the changes in this area are approved. The new layout is changed as shown below:



As we can see, the extension to the riser now starts from the top of the 5th floor slab (previously from 5th floor ceiling) and some room space is now allocated to the riser. To make up for that, the wall has shifted 500mm to the east and shifted some space from the storage room next-door, to the 514 room. Note that as a result of these changes, there is an area, which is in the riser now, but because of the layout in the 6th floor, it ends at 6th floor slab. In other words, the riser will be closed at the red area, and in my opinion that is a dead space.

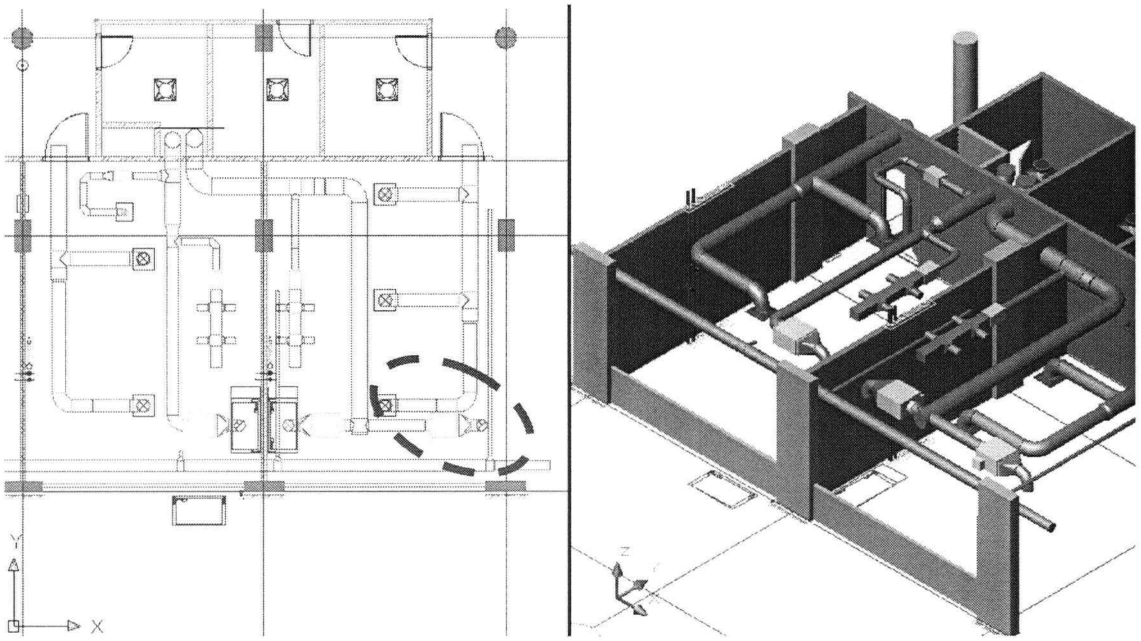
I asked the MEP rep on site (Kevin) whether the duct's connections to the air diffusers are "T" or "L" shaped. He contacted Gary, and the response was that they are different on a case-by-case basis. Therefore, they should be asked, case-by-case from Gary. And later on he mentioned that this is not a point of concern, since if worse comes to worse, they can always use flexible ducts in those areas.
In addition, the location of the exhaust grills needed to be asked and clarified. (See below)



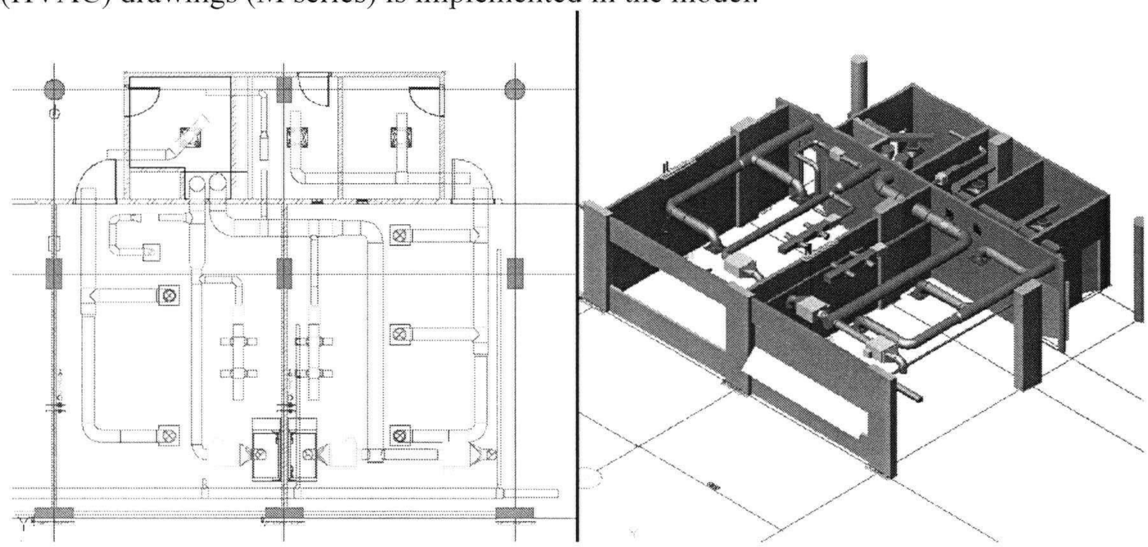
This was later fixed based on the information available in the architectural drawings. (A908)

Incorporate Change to Grill Elevation

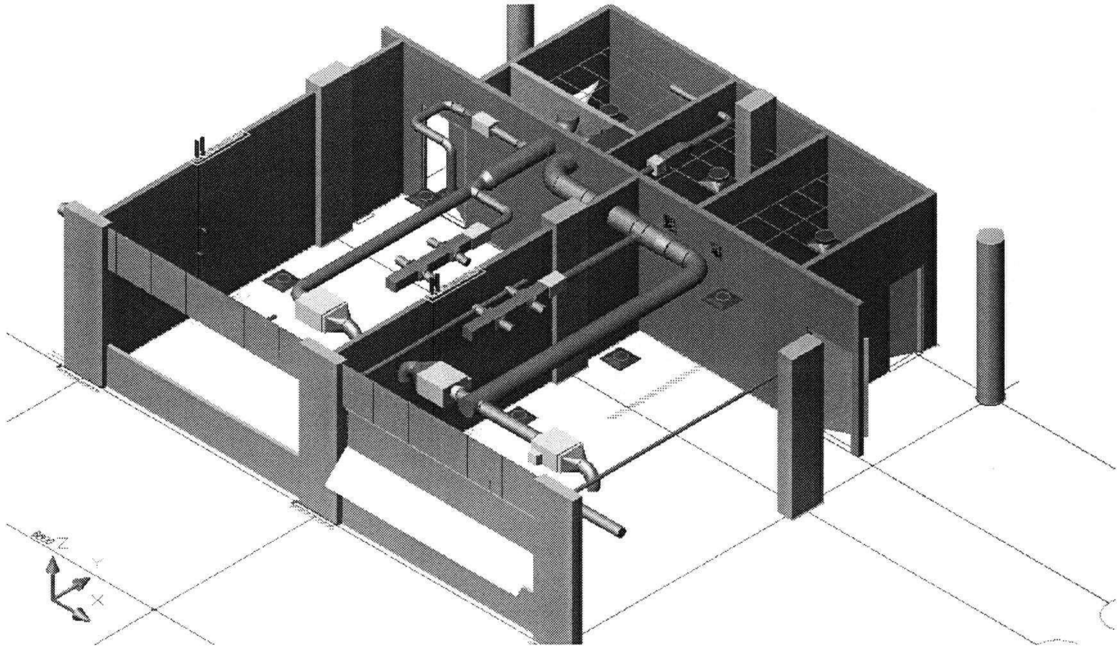
Later on in the process the elevation of lab grills was set by architectural drawings (at 2100 mm AFF) and the location of it was changed to match the schematic location shown on the A908 drawing for the "extract hood" location. Thus far, the progress regarding implementation of the information related to mechanical systems is demonstrated here:



As we can see, the only place that needs attention is the air-valve AV-5206 which is located very close to the supply run and is almost in contact with it. In addition, the 100mm in diameter exhaust line, which is running into other ducts, if run at the current assumed elevation (3200). It was further considered, with respect to the windows as well as curtain walls and it was validated. All the information regarding the Mechanical (HVAC) drawings (M series) is implemented in the model.



Based on the talks with Martin, the electrical conduits will cross the riser from the lab [room 508] into the ceiling space of room 514 to go up to electrical room. For that reason, they need a 600(W) x 200(H) mm of space when crossing that riser. This is only possible if they cross below the main exhaust ducts-elbows.

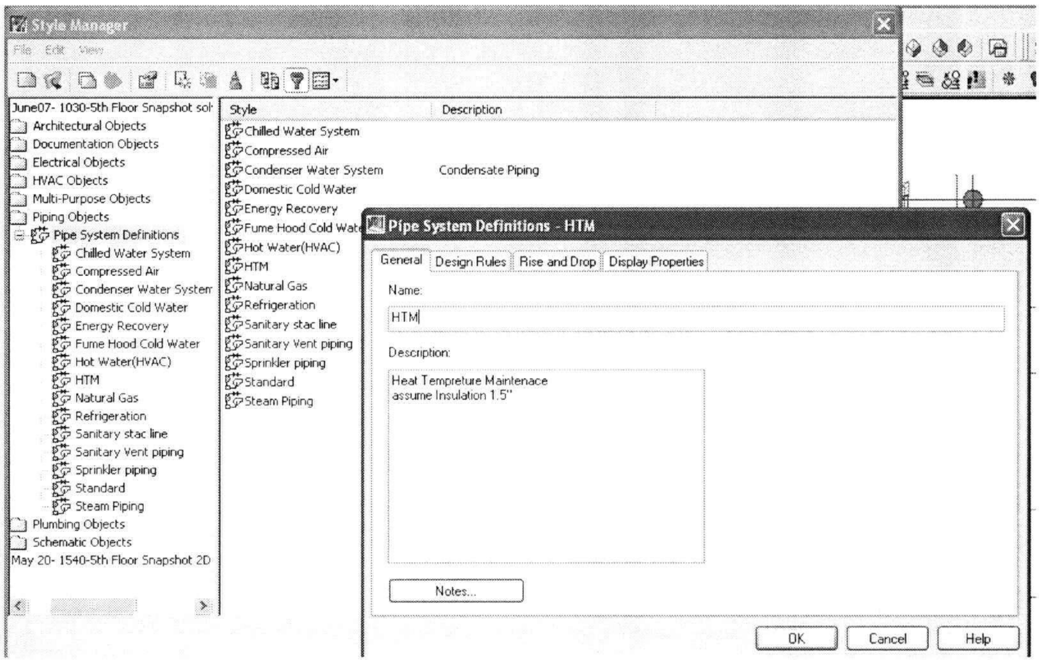


At this point, the space available between the bottom of the 500 mm diameter exhaust duct and the ceiling finish level of 2850 in room 514 is about 100 mm. considering the 25-50mm clearance needed for the ceiling; we should raise the exhaust duct further up another 125-150mm. This means that the whole exhaust system has to shift to a higher elevation.

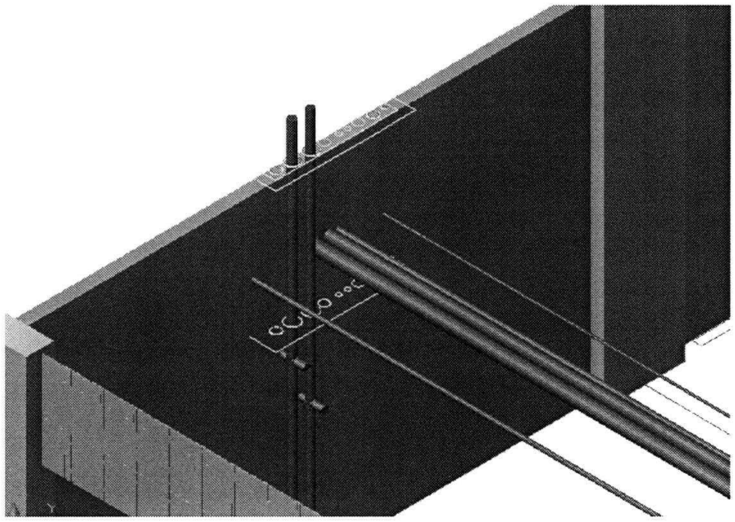
This was implemented and appeared to resolve the problem. However, when talking to the architect he had some concerns regarding the looks and presence of those conduits at that elevation. He mentioned that the design should account for aesthetic considerations regarding this situation.

Plumbing System

To start implementing the plumbing system, I started with defining each particular system. The software uses different styles to differentiate between these different systems, and it would be hard to manage them if they are not defined and distinguished by different styles. During style definition, we could also document any assumption we made, which would assist in maintaining consistency through out the modeling process. It is important to consider assumptions like the material used, connection type, the gauge of the pipe, insulation assumed, the main elevation, etc.

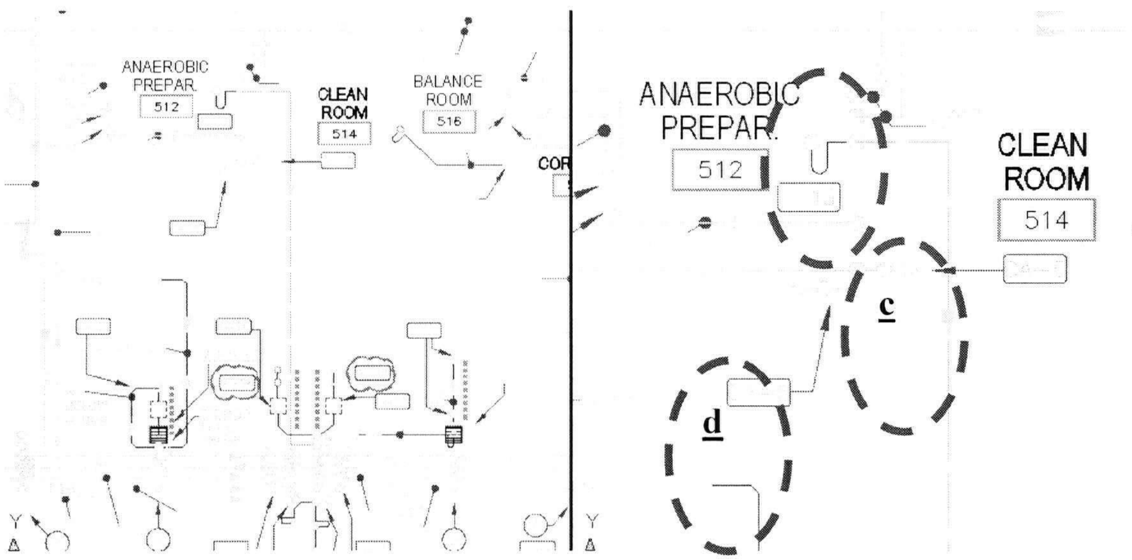


After defining the systems, it is time to assume their order. I should mention that the order and arrangement of some of the pipes in this hot spot, is different from architectural drawings to plumbing and mechanical drawings. This was confusing and if not addressed, could later result in coring and additional work during construction. It is important to figure out and maintain an order for the pipes, since the sizes and routing of each system is different and it will effect the interference assumption, as well as placement of the sleeves in the slabs.



In the area of room 512 and 514 where the wall between the two rooms was shifted 500 mm to the east and the duct has changed, there are a few questions raised that need to be addressed and changes to be applied to the plumbing drawings:

1. Fist, in the plumbing drawings, room 514 is referred to as the cleaning room, while in the architectural drawings it is a storage room. This was communicated to the consultant so that it will be corrected from now on.



2. Then, due to the changes in the location of the wall and shape of the riser in the room 512, the layout and routing of the plumbing elements should be reconsidered.
3. The compressed air line going to the room 514 should be checked for redundancy if it is a storage room. When discussed with the consultant, he confirmed about there being a storage room, but reasoned that since the user might want to change

the usage of that room at some point, it is better to have that compressed air pipe in there, just in case.

In addition, the following issues were raised with regards to the labs:

4. The floor drain has no P-trap in there
5. The size of "sanitary waste" pipes for the fume hoods and the sinks are not indicated in the drawings. When asked the plumbing sub, he mentioned it is usually based on common practice; in this case, they are 2" pipes.

Note that these issues were all communicated to the Mechanical sub (Gary) to give a heads up.

Sanitary Waste Run

The sanitary waste run in room 516 (Balance room) which connects to the floor drain of the Distiller room on sixth floor (room 616) has no way down in the 4th floor. (at least not in the drawings.) This was confirmed as a mistake, and the plumbing sub was informed to issue an RFI about it.

- The details for the sanitary line running around the "island unit" in the Lab 508 was not clear and needed to be discussed further with the designer and Gary. It took lots of discussion and collaboration to synchronize the designer's insight, the perception of the builder, and the model together. It took three iterations to develop the proper model design before finally satisfying all parties. If this re-work would happen in real world and not the virtual model, it would cost more time and money.

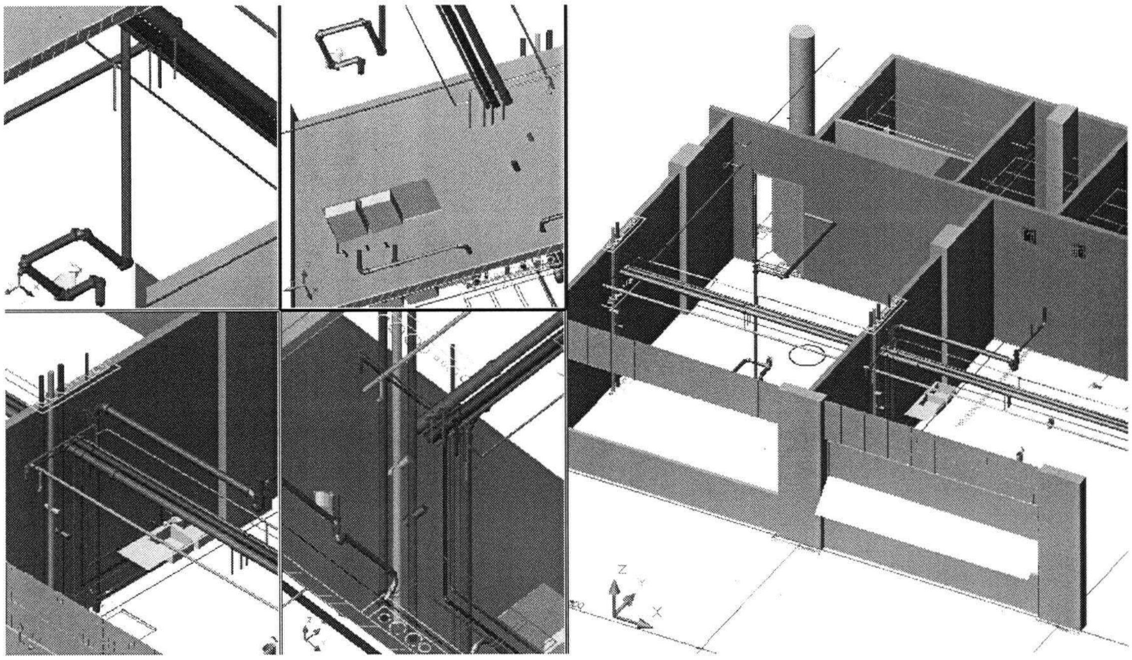
- In the plan view (P106), service branches and the valves come off on each side of the wall. However, in the elevation detail view (P202), the sinks and other benches are being fed through the walls. This could create confusion and when I asked the consultant, he mentioned that they were originally on both sides, but then it was changed to one side only. However, not all the drawings were updated to indicate this.

- The Valves shown on both side of the wall on grid line 4 are marked as (type 2). However, I think that (type 2) is for when the pipes have to be connected to a bench and on this wall, we did not have any sink or fume hood. Therefore, it would make sense that the specs at this point be modified to (type 3) (like the 6th floor). The same applies for the "island units" in room 522 and 506. This has not been clarified yet.

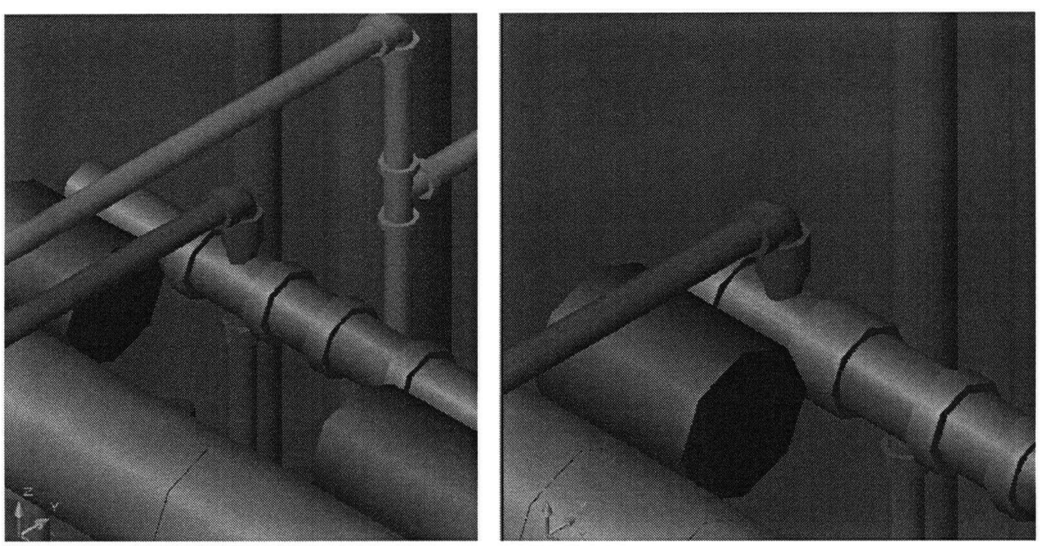
- The Vent stack near the grid line 5 is missing size information.

Refine the Locations and Elevations of the Runs and Pipes

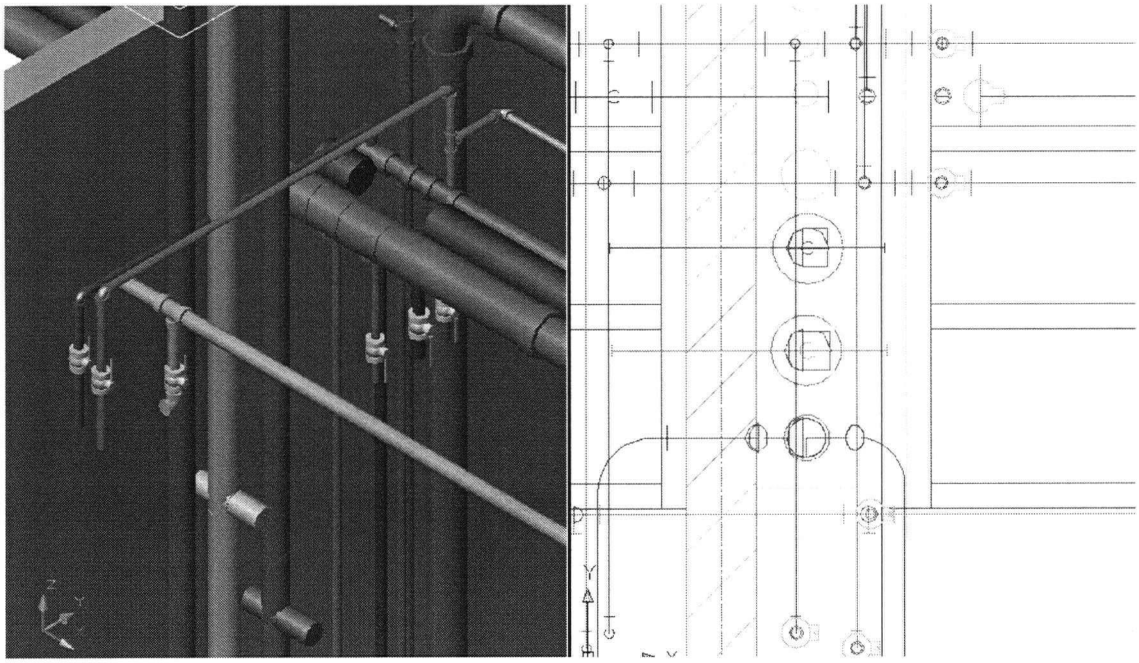
I implemented all the information in the plumbing drawings in the model. Next step would be to refine the locations and elevations of the runs and pipes.



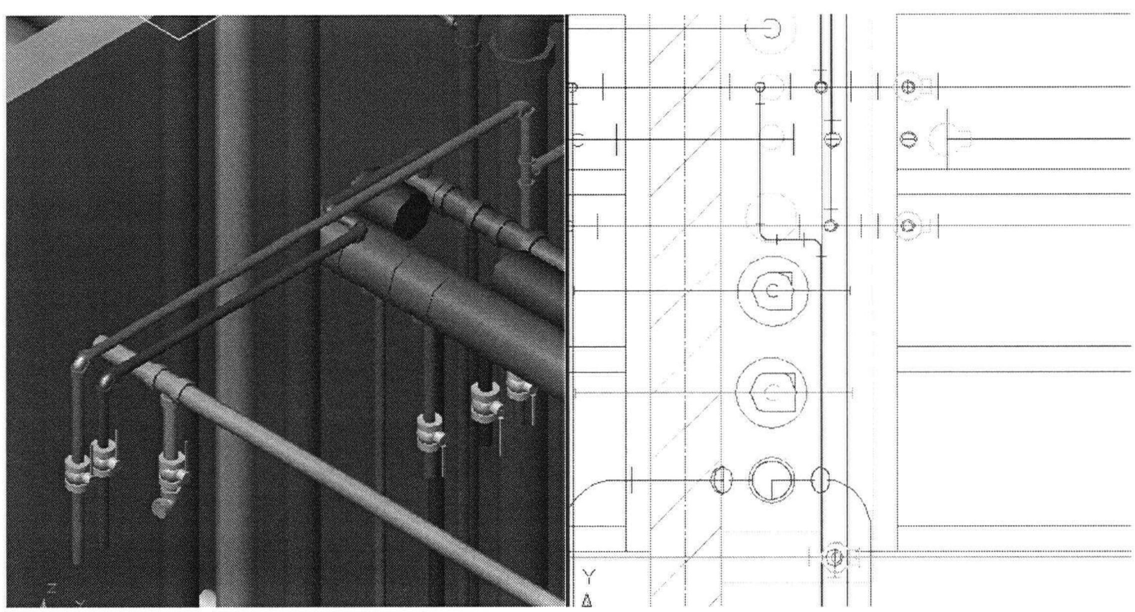
Talking with Kevin, the Plumbing foreman, I discussed details of fittings and piping. For example, there was a place that based on the indications in 2d drawings, I had used a cross fitting in the 2" Compressed Air pipe, to get two ¾" pipe branches.



But when I actually did that, it would interfere with the vertical stacks



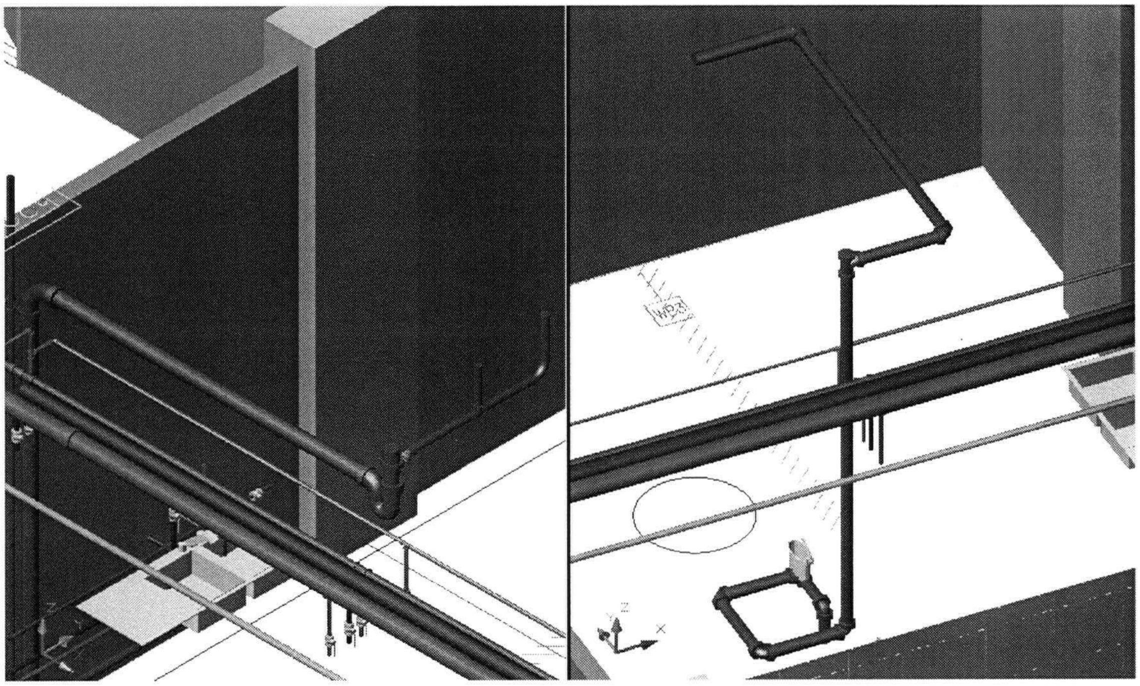
As a result, the run that is supplying the fume hood should be modified or redirected. Kevin suggested having both runs from one single 1" "T" fitting and then get two ¾" runs out of that 1" "T". For a solution with minimum changes from original drawing, this could be a suggestion. This would resolve the issue, and because there is no change in size involve, does not require an RFI.



I also discussed the current layout of sanitary waste for the floor drains and cup-sinks. What is currently in the drawings, accounts for the floor drains of the 6th floor labs. In

Lab 518 it also accounts for the cup-sinks of the 6th floor waste, but not for the cup-sinks located on the island benches in the 5th floor.

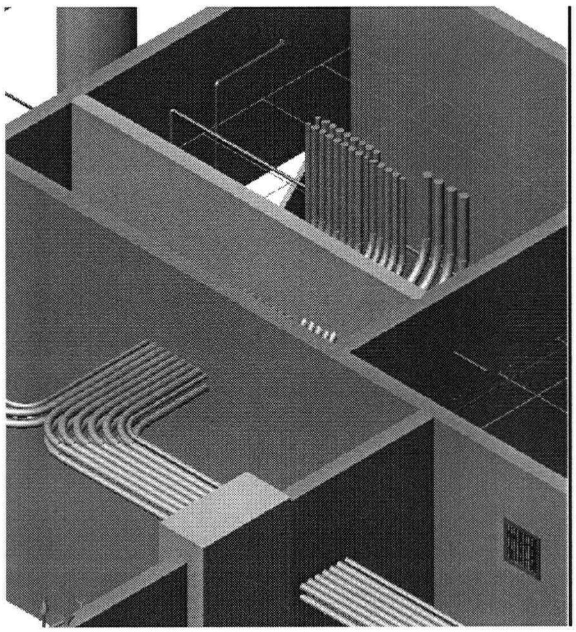
In lab 508, it shows neither 5th nor 6th floors cup sinks. Kevin also mentioned that venting them might be an issue.

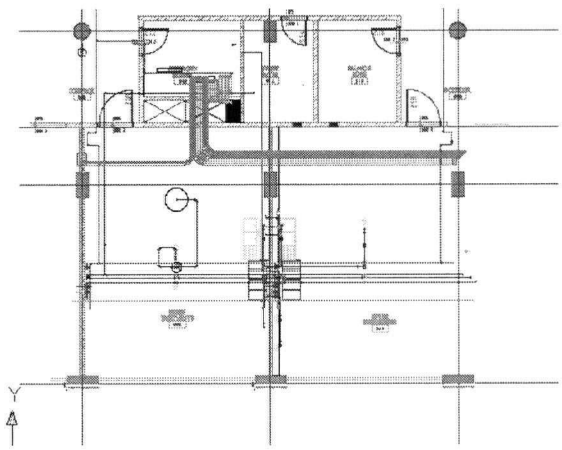


Electrical System

<u>3D Electrical Conduits</u>

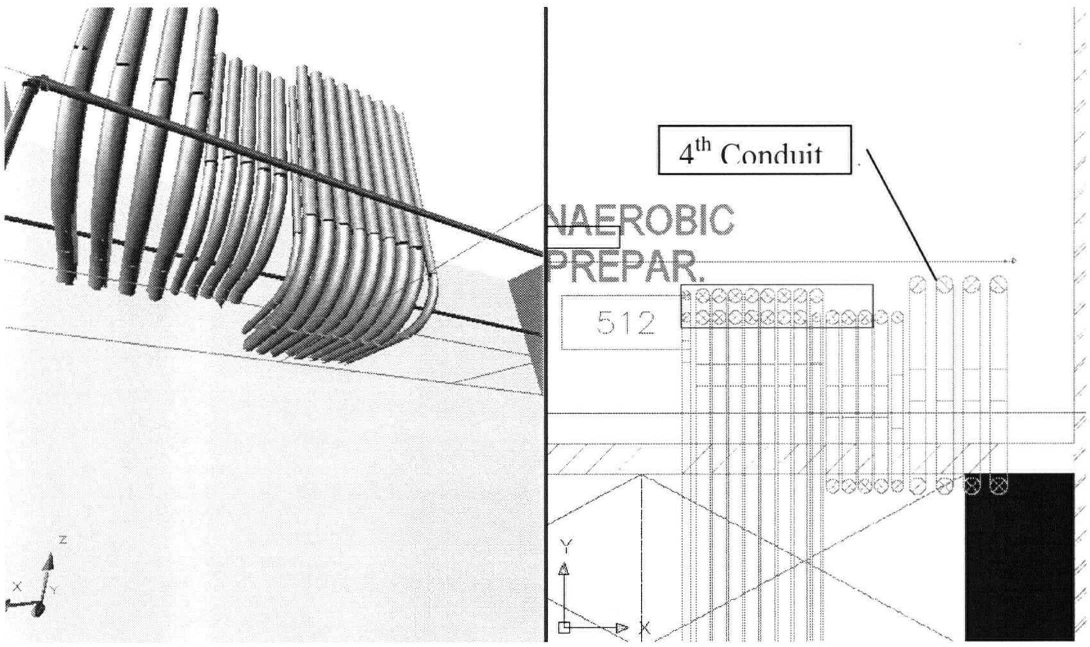
The next step was to implement the conduits.





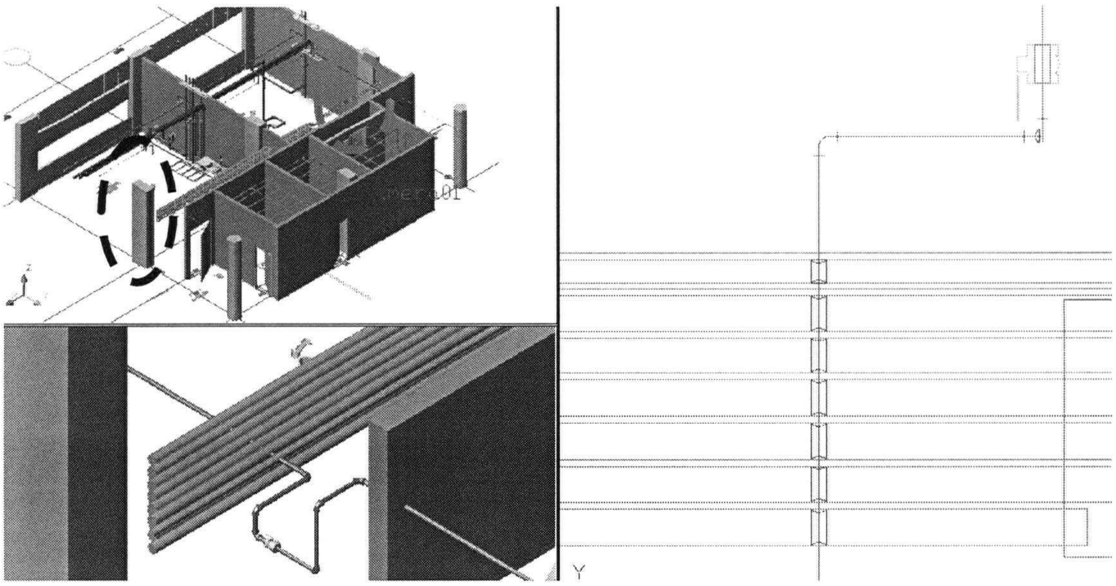
Some points regarding the conduits to be considered:

- As you can see in the next picture, the left side, the conduits had to be offset to the ceiling space of the room 512 and therefore, should do that in an elevation above 2850 (the elevation of ceiling in this room). This objective can only be achieved in the layout shown. However, the penetration through the wall has a disorganized way, since it is the elbows that are penetrating the wall. When discussed with the electrical sub, he confirmed that this is what they will have to do, and that in execution, there will be an opening in the wall to accommodate the penetration of elbows.

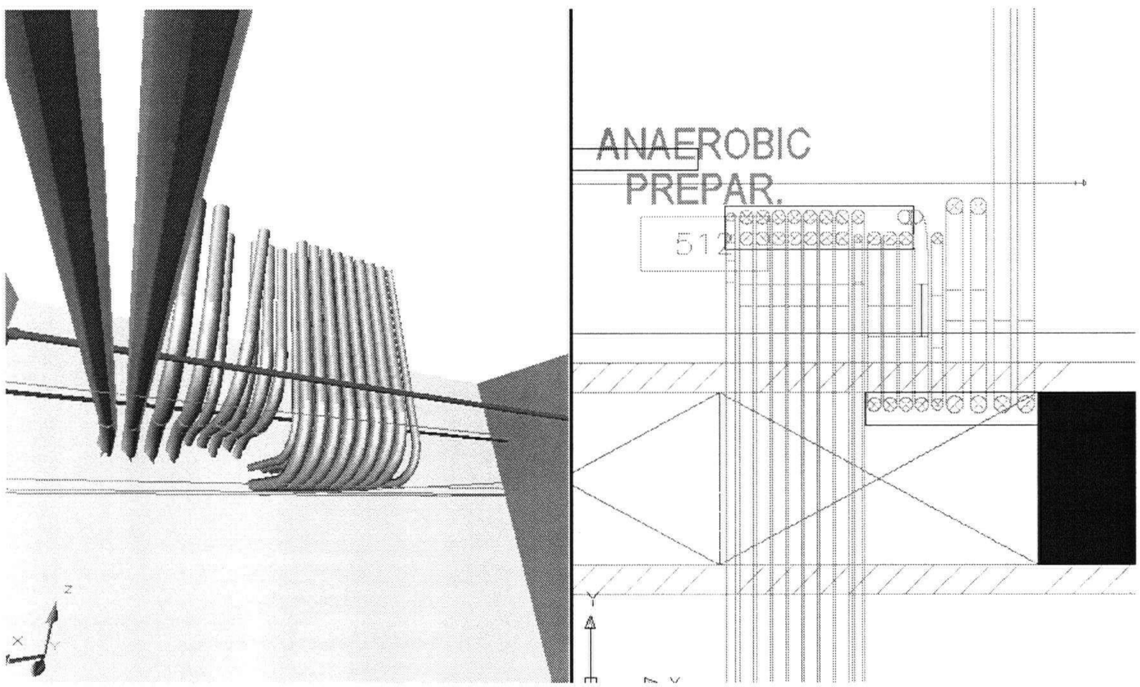


- The right side of the picture shows a rectangular that represents an opening in the 6th floor slab, where the conduits have to go through and connect to the equipment in the electrical room. There are 4 conduits coming from the 4th floor that have to go through this area, but as we can see, the 4th conduit is left out.

- Interference: at current layout, we can see that the conduits and the gas pipe running in the lab do have an interference problem. Since the conduits elevation is strictly restricted by the ceiling height in Room 512, and the exhaust main ducts in the labs, the Gas pipe elevation was changed to solve this issue.

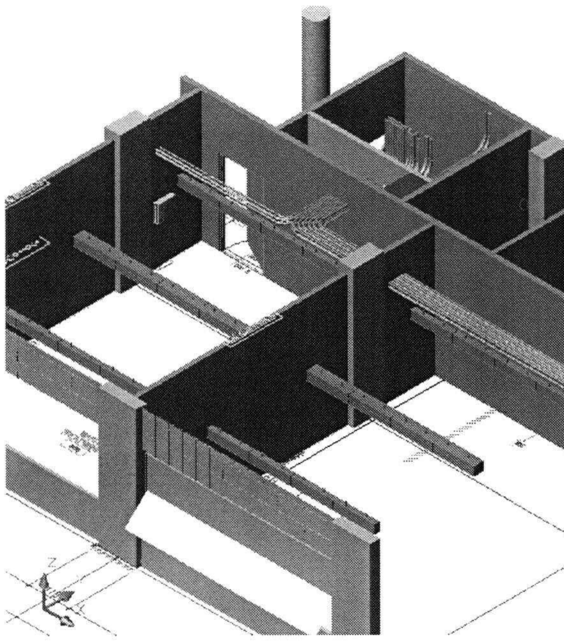


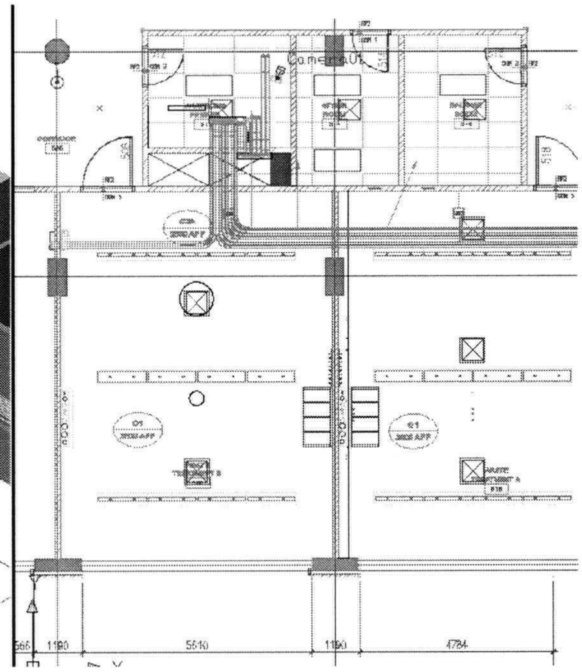
- Another problem was that the last two conduits were located in the black square which means they are out of the electrical room area in the 6^{th} floor and would cause extra 90 elbows to get them back into the electrical room. This would not be possible according to the code. (Code allows for 4x 90 degree turns in each cable/conduit line, from box to box).As a result, we had to shift the cables. Based on the 3D model, we realized that we can shift the cables and the opening on the 6^{th} floor to the east and nothing prevents us of doing so, up to 5 inch. That would provide space for one of the conduits. To provide enough space for both of the two, we squeezed the 5 last conduits. Furthermore, to bring the 4^{th} floor conduit which was left out, into the 890 opening in the 6^{th} floor, we tilted the vertical part from the elbow, just 5 degrees. The resulting layout is shown below:



- Note that the offset of two rectangular openings from grid 5 in 5^{th} and 6^{th} floor slabs are 1550 and 2170 mm respectively. ***This is one of the key contributions of this snapshot.***

After adding the electrical panels and Pendant Fluorescent lights, the electrical model is complete.

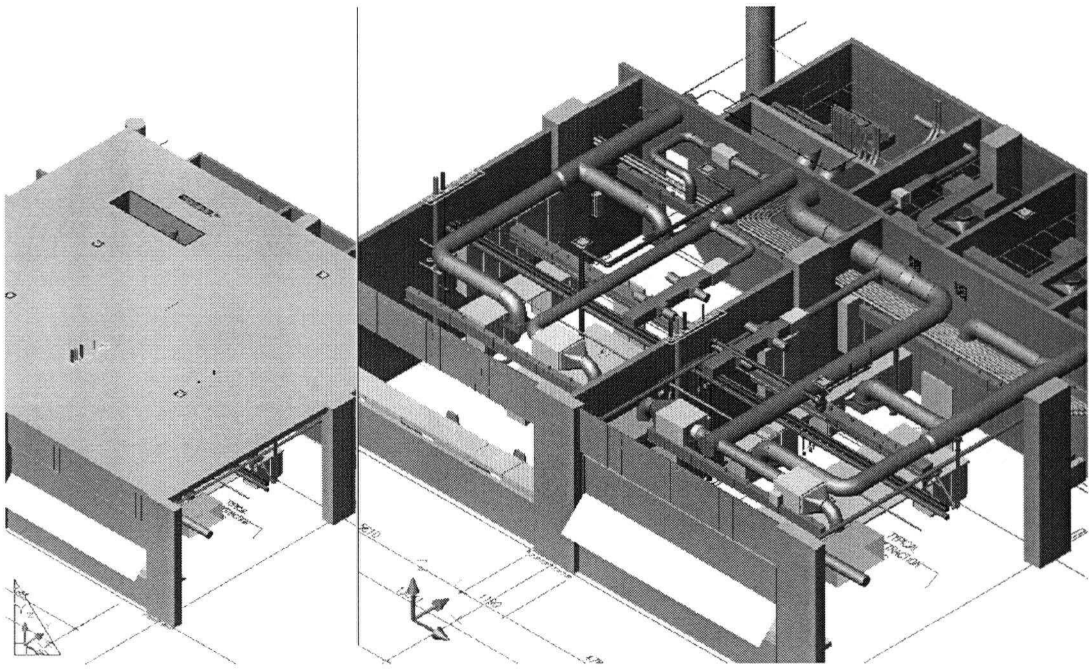




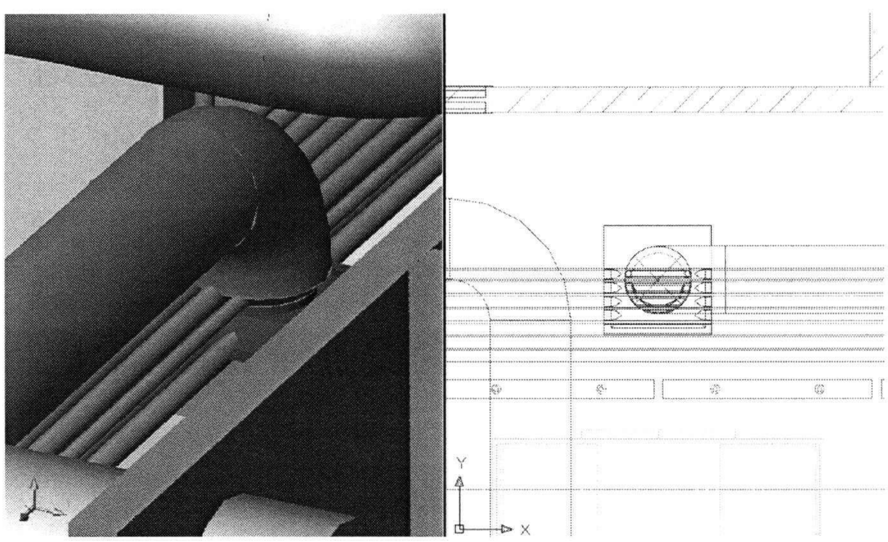
3D Conflict Detection

It was time to put all the layers together in the model and deal with the interferences, and final detail fine tunings. We can see all of the systems together, together with the opening and sleeves necessary in the slab.

Interestingly, for a crowded model like this, we only detected 3 major interference points and few other ones with much less complications. This is mainly because many others were identified and resolved along the way. Having a closer contact with the trades was also a reason.

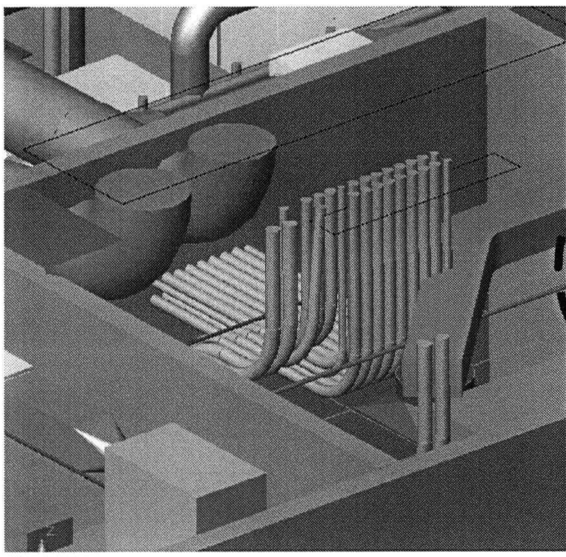


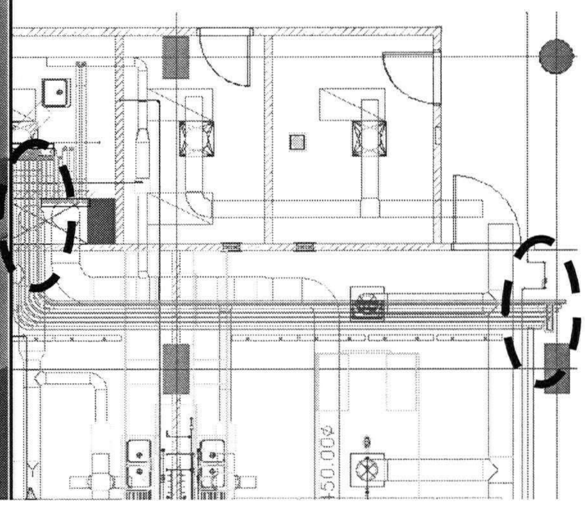
<u>I0704-1</u>
The first interference was between the supply duct and conduits.



As we can see in the picture above, the conduits are running into the supply duct and its diffuser. Our conduits have many constraints on them. Horizontally they are constrained by the placement of the electrical panels in the room. Also moving them might cause interference with the fluorescent lights (see picture below, right).

Vertically they are constrained by the ceiling space in Room 512 and the exhaust ducts in the riser adjacent to it (below, left). If we move the conduits down it will be below the ceiling space. We have a little space to move them up but that would not solve anything. And if we raise them too high, we will have a problem with the exhaust duct

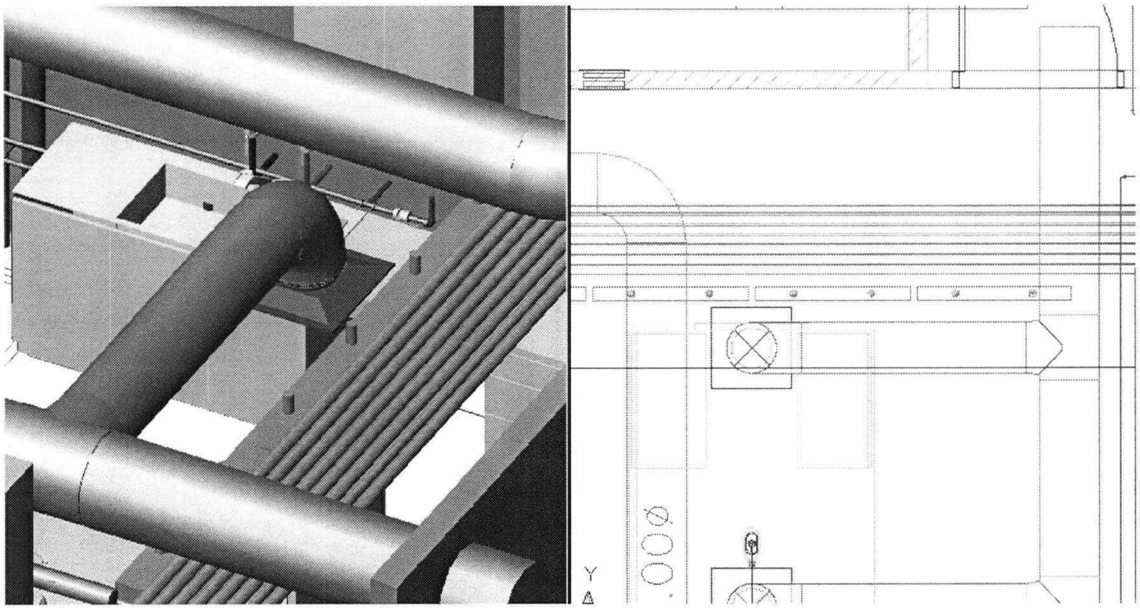




In this case, the diffuser and the duct are constrained vertically, to our service space boundary in the labs. And if we raise the diffuser up, the air will be disrupted by all the conduits blocking the way.

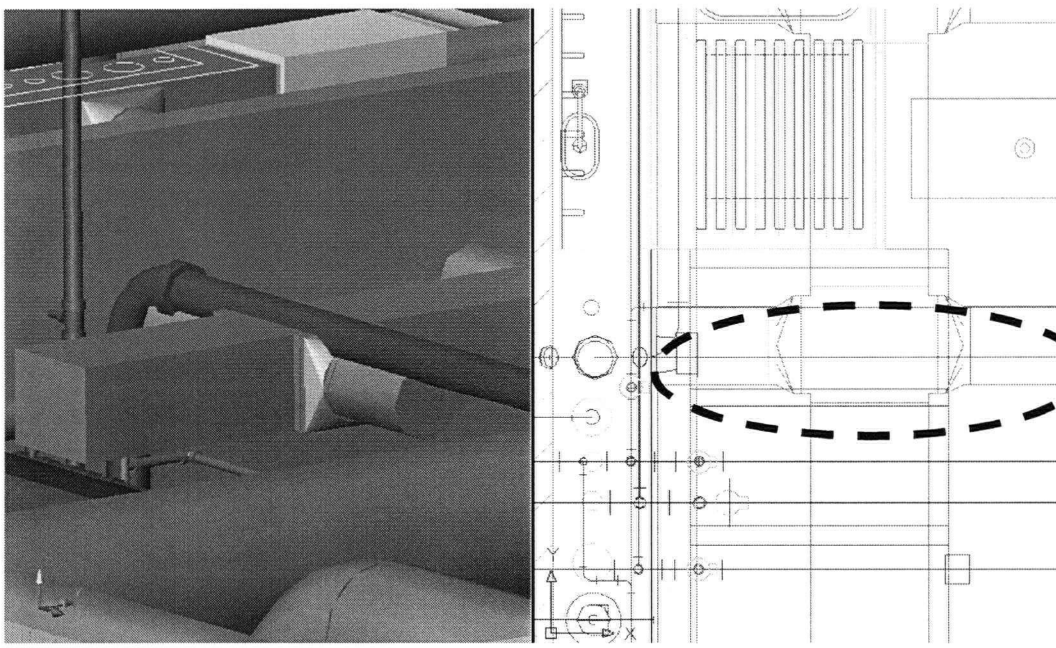
Probably the best thing to do in this case is to shift the branch containing the diffuser horizontally. This should be done considering that we can shift it to the north, but we will get too close to the wall, and we can also shift it to the south, which will end up right on the table (the island unit). For the moment, I chose the second option and moved it over the desk.

Note that on the left, we can see another point of interference between the conduits and the supply duct in room 512. This however is not important since according to the HVAC sub, the ducts in the ceiling space of rooms like 512, can be flexible ducts which will solve this problem. Also, there is lots of manoeuvring space in that room to reroute the duct. My advice is to change the placement of the diffuser in that room. This was communicated to the architect for further action, but is not resolved in the model.



I0704-2

The second major interference is between the sanitary drain run and the return exhaust air duct in the Waste Treatment Lab A (room 518).

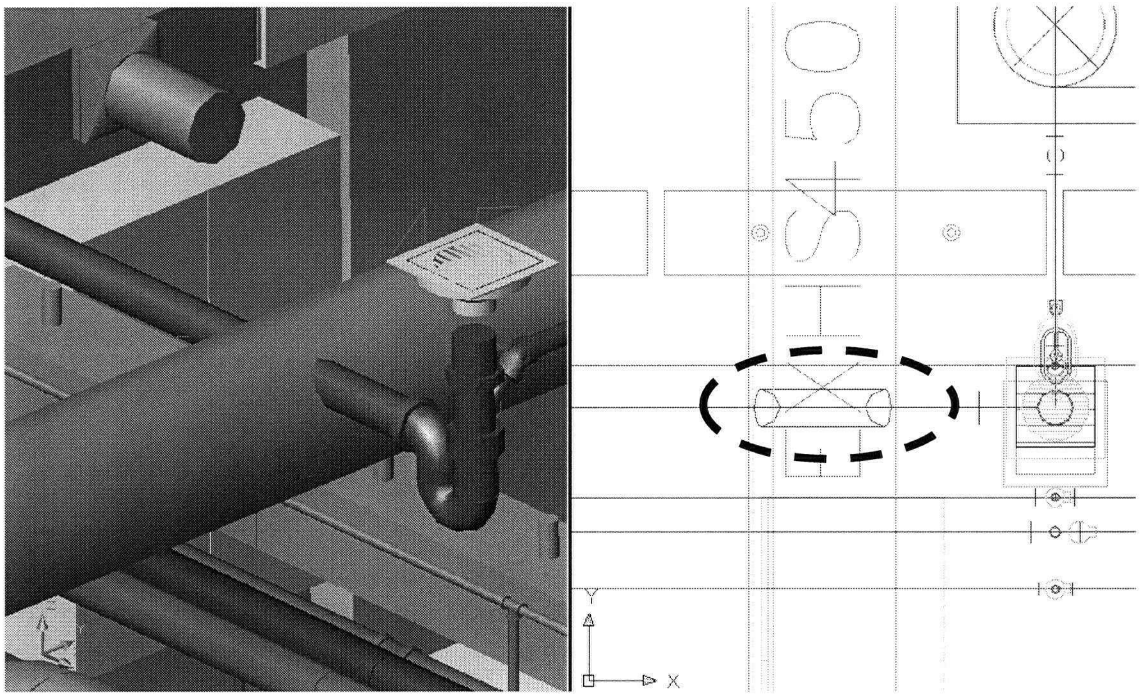


The Sanitary pipe is constrained horizontally (because of the location of the floor drain, and the stack) but it can move vertically. Nevertheless, it should be considered that shifting it to a lower elevation should not go beyond the service space limits, and when raising it to a higher elevation, concrete slab, the floor drain above, and the p-trap should be considered.

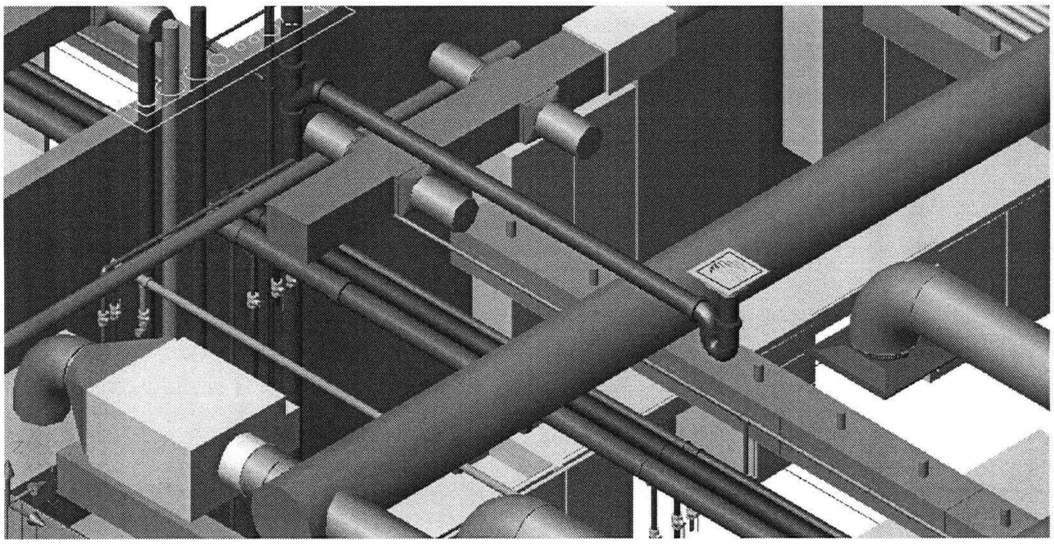
The duct however, does not have any major constraints but changing its elevation will likely cause the rest of the exhaust system to change. Perhaps the best way, if necessary, is to use an offset, right after the air valve so that the rest of the system remains intact, and we can clear the pipe. But it does make sense to try changing the simpler element first. In this case, that would be the sanitary run.

<u>I0704-3</u>

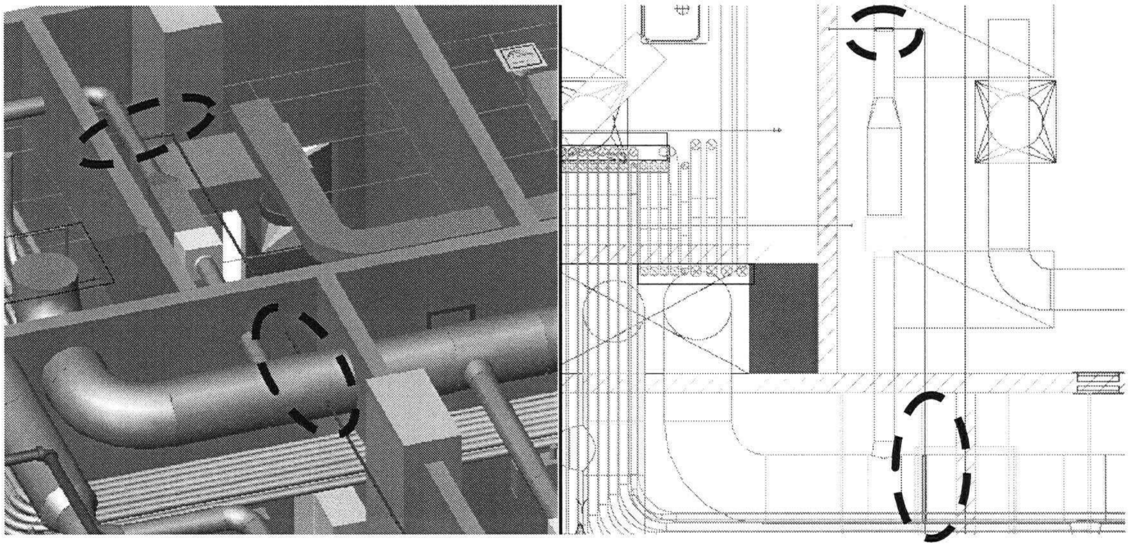
The third major issue highlighted was the interference between the sanitary pipe and the fume hood exhaust run. This has all the similarities of the I0704-2, except that this is a main exhaust line and any change in its elevation will affect most of the system.



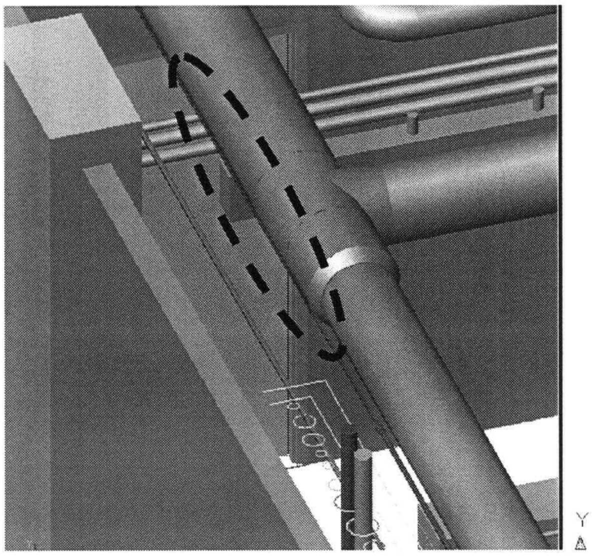
Again, I believe that changing the elevation of the sanitary line is the better solution. The resolved situation is shown in the text image we can see that with raising the elevation of the sanitary line, I0704-1 and 2 are both resolved.

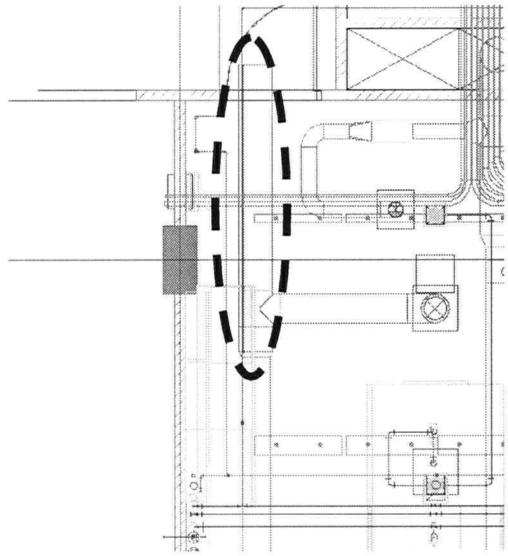


Other minor issues revealed in the model include the interference of the vent pipe, running from room 512 down to lab 508 with the ductwork in 508 and 514

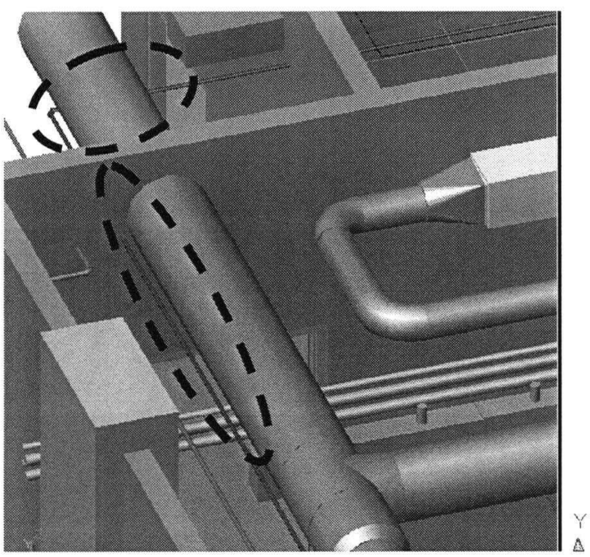


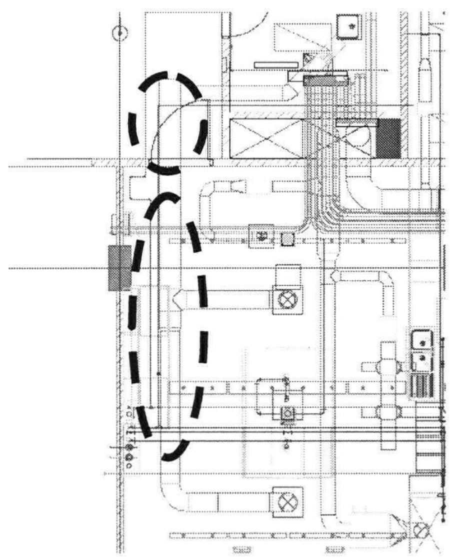
This pipe can easily be redirected or shifted to a different elevation as necessary. I increased its elevation another 300mm and it was resolved. And another one is the interference between the "compressed air" pipe and the duct work in lab 508 which looks pretty bad in the 2D drawing (right) but as we can see in the 3D, it is barely touching the duct and with a little shift towards the wall, it will be ok.





When I shifted the pipe I noticed that it would still have a problem with the extension of the supply duct in the corridor (see next picture).We can see that in a 2D drawing, (right) it still looks like it has interference, but in the 3D (on the left) it is clear that there is no problem there

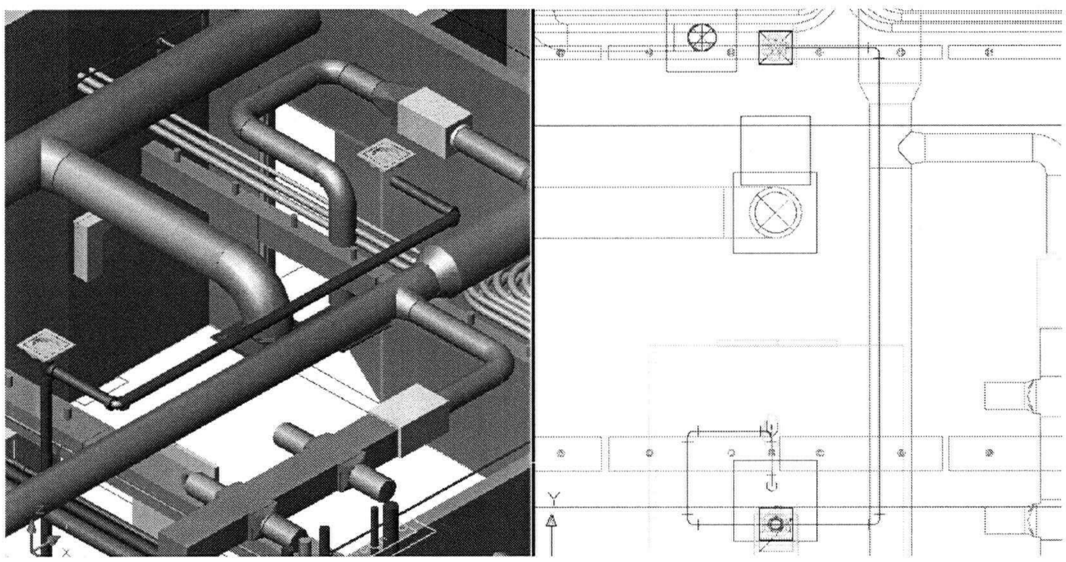




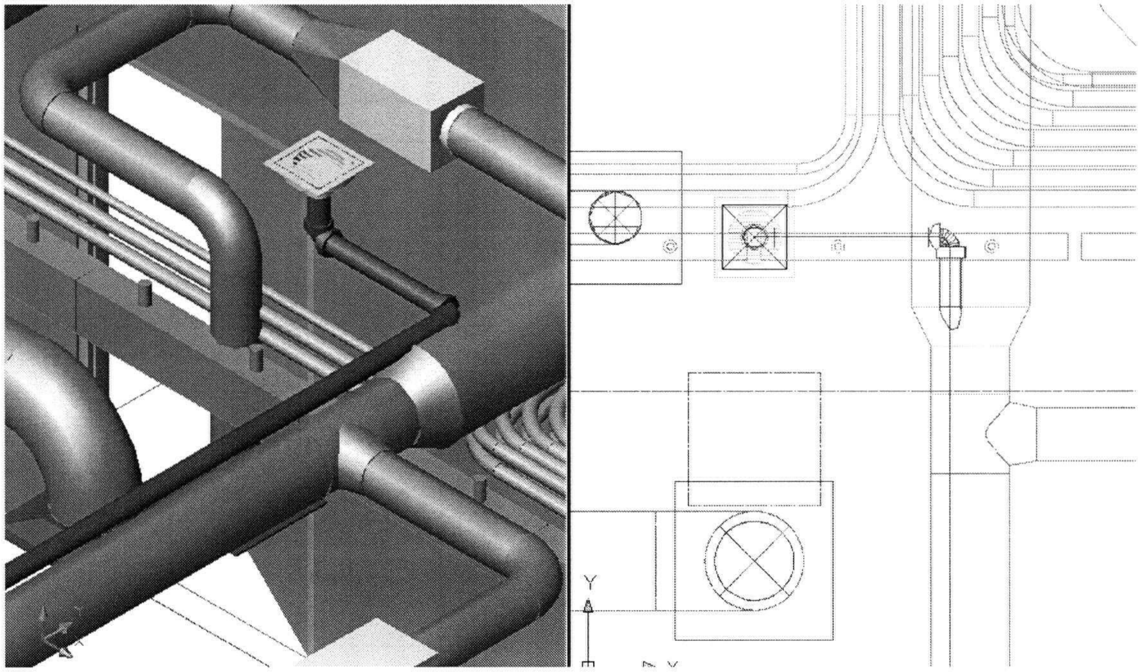
Since the scope of the model is limited to the lab itself and not the corridor, this could remain un-noticed. I believe that this is one of the problems of partial modelling. Nevertheless, this requires a change of elevation in the compressed air pipe. Based on the current model, (0704-1200) the duct is occupying the space from elevation 3175 to 3615 and therefore we should go either below or above that. Now since the conduits occupy the elevation from 2860-3200, this means that if we want to pass below the duct, somewhere before reaching the conduits we need to offset the pipe to a higher elevation again. Therefore, I decided to go to a higher elevation and solve the issue.

Execution conflict

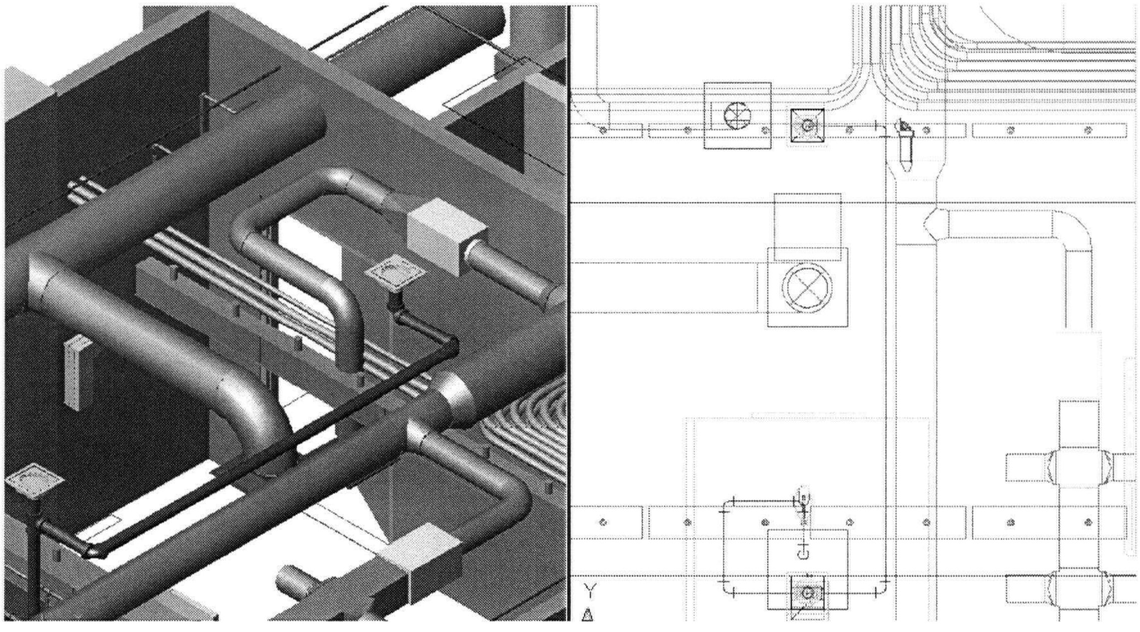
While evaluating the sanitary line in terms of reality of connection of floor drains from the 6th floor, to the runs and pipes below the slab, I realized that the sanitary run in room 508 needed to be relocated. The reason is that when accounting for the fact that the drain needs a 6" pipe and then an elbow to should be connected to that run, this means that the real elevation of this run will be lower than what is shown here



When adjusting the elevation for the actual and practical run, we can see that the pipe will interfere with the exhaust ducts



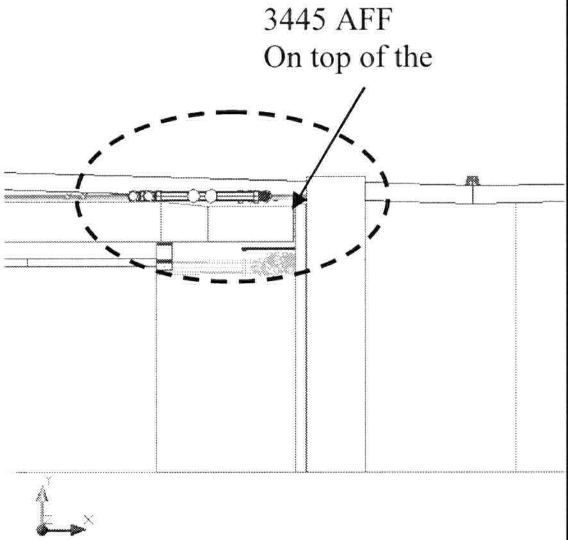
To resolve this issue, we might be able to use a shorter pipe (at the marked area) than the current 6" (say 100 mm length). However, a safer and better solution is probably to shift the interfering pipe to the east and avoid the duct. I used this solution and it is shown in the next image:

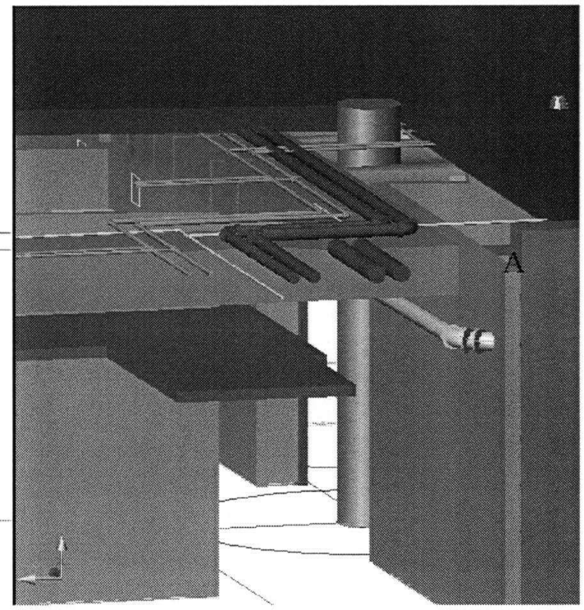


6th floor Corridor

Finished floor heights and the slope of the roof slab

While Building the Model it was realized that the slab in the 6th floor is not only variable in thickness, but also is sloped. Therefore, the finished floor height available will be less than expected. That was mainly the cause that the Hot Water Supply and Return line and the Heat Recovery/Chilled Water line would have to be executed below the duct, not on top of it as shown in schematic drawings. The picture below-right shows the location of these pipes based on schematic drawings. The image on the left shows why they cannot be there and how they interfere with a thicker-sloping-roof slab

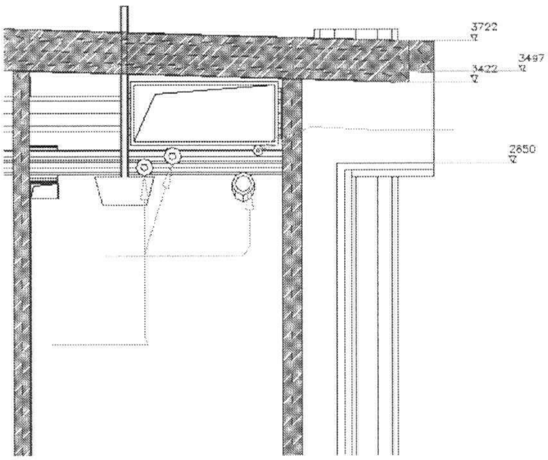


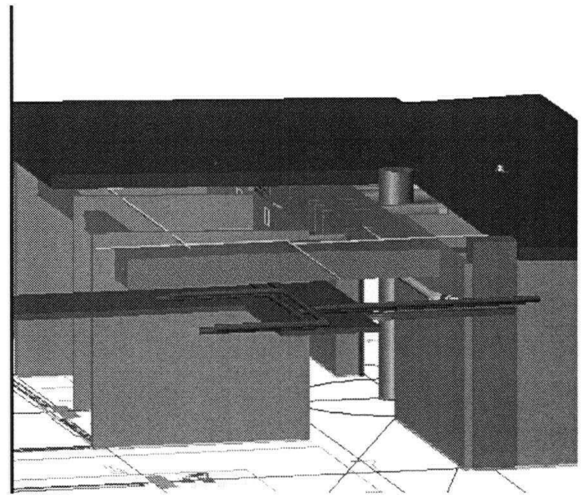


The slope was projected in the model, and it was calculated that the available height from top of the 6th floor slab to the bottom of the roof slab at the intersection of wall and roof slab [Point A] is 3445 which will in turn, dictate the constraint on duct 90 degree straight elbow fitting elevation at the closest corner.

Chilled Water/Heat Recover Line

Furthermore, it was realized that the Heat-Recovery line will probably not fit in this floor, and one suggestion was to move it back on the roof (where it originally was, before the "cost saving revisions").

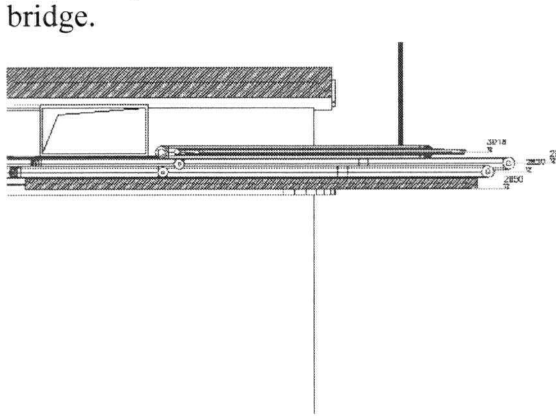


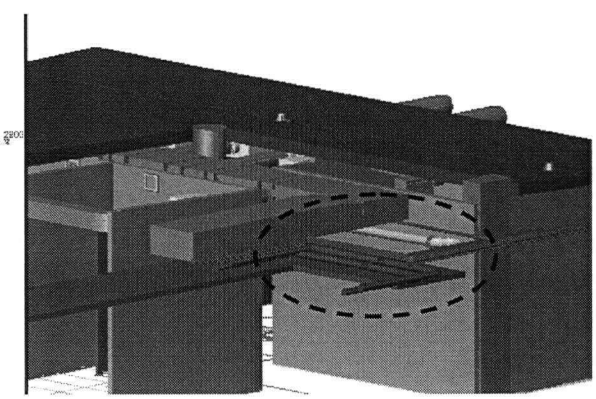


However, this conclusion was mainly based on the concept of avoiding "air traps" to obtain a good plumbing practice. (Once you create a vertical straight or reverse "U" with your pipes, air could be trapped and cause problems in your flow) In general, the pipes should avoid air-traps, which are cause by the "U" shaped runs (down-straight-up or up-straight-down runs). In the event where this kind of layout is not avoidable, other accessories should be added which needs 6"-8" of space and costs money.
Further discussions with Kevin (plumbing foreman) indicated that there are ways to make it work. Therefore, before switching the chilled water back on the roof, this needs to be carefully examined.

Floating Ceiling Elevation on the Bridge

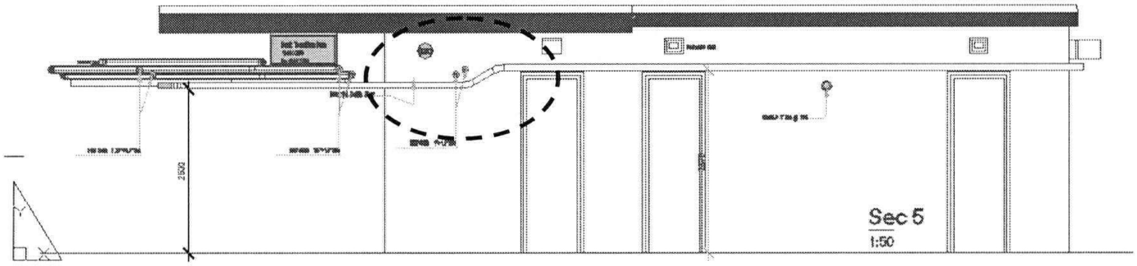
While the model was being built, the elevation of the floating ceiling at this floor, in the bridge area in the west core, was set at 2850 AFF. Later on, when the model was ready to detect the interferences, there was some changes issued on the IFC drawings, and this elevation was raised to 3000AFF. In addition, the previous rectangular shape extended to the current "L" shape. Further examination of the model showed that neither of these would work, and based on the discussions and reasoning of the model, the elevation of that ceiling was lowered to 2650 AFF. This was with the confirmation of architect.
Next image illustrates the isometric view and a cross section of the ceiling space at the bridge.



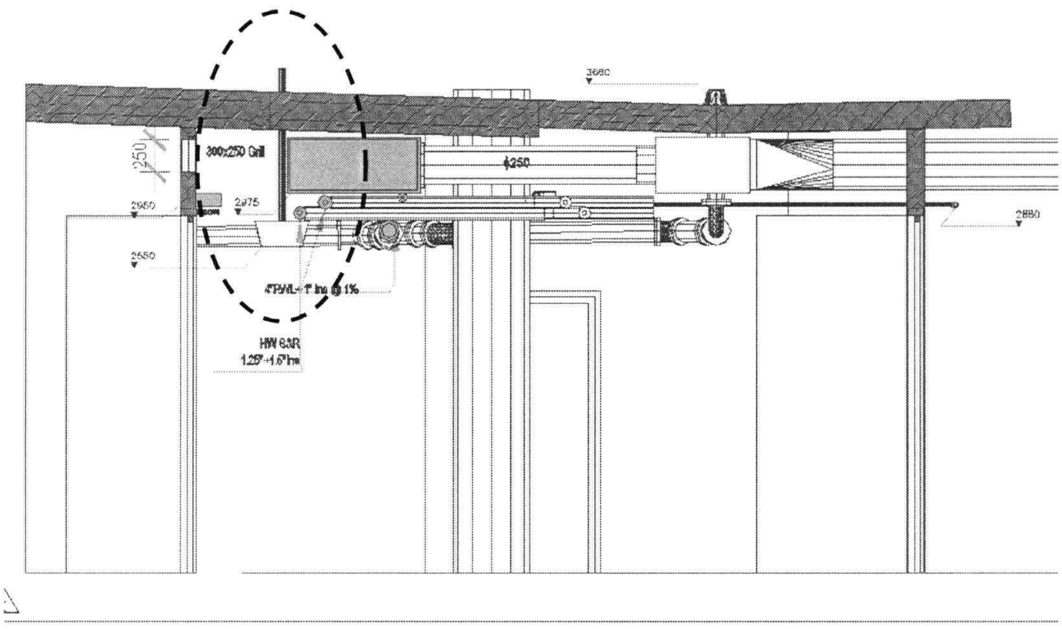


Note that accounting for insulation, and running staggered, the HW S&R 1 ½" line will occupy a space of 210 mm height to accommodate the crossings of supply and return lines over each other.
All of the above was discussed with the Architect and the decision was to lower the floating ceiling to 2650, with a very tight space to run the pipes, duct radiant panels and lightings. The current situation works, but has no room for errors.

<u>Cable tray clearance and layout</u>
We noticed that by code requirements, a clearance of (610 X 300 MM) is necessary for the cable tray, and should be provided.
The horizontal run of cable tray seems unlikely. It should run above 2850 A.F.F elevation to avoid office doors but at the same time, should avoid the 250mm round duct, the main duct and HW S&R pipes which are all tight from 2750 up to the slab. A possible solution would be that it runs above 2850, until it passes the last door, (609) then it drops to 2600 to go under the ducts and pipes. This is shown in the below snapshot.

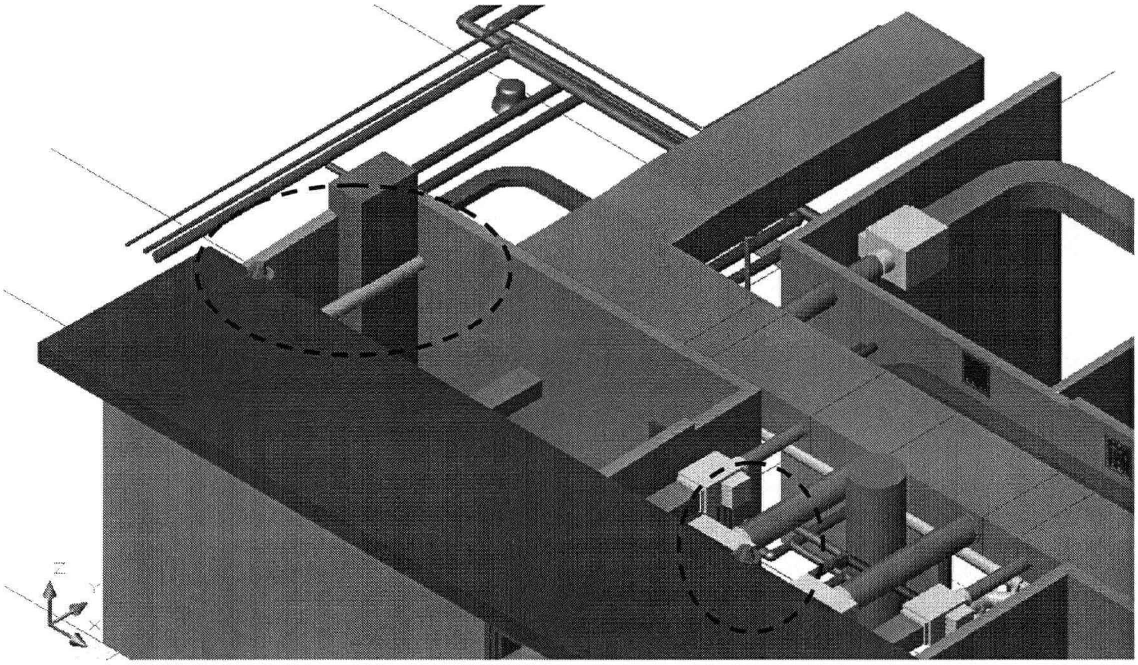


<u>Arrangement of lighting fixtures</u>
It was realized that because of the size of the corridor and the duct, it would not be possible to hang the lights in the Centre Line of the corridor



The exact poisoning of the roof drains on the roof:

We can see that the current location of the roof drains will cause the interference of the pipe with the concrete column. The easiest way to avoid this is to shift the roof drain to the east.

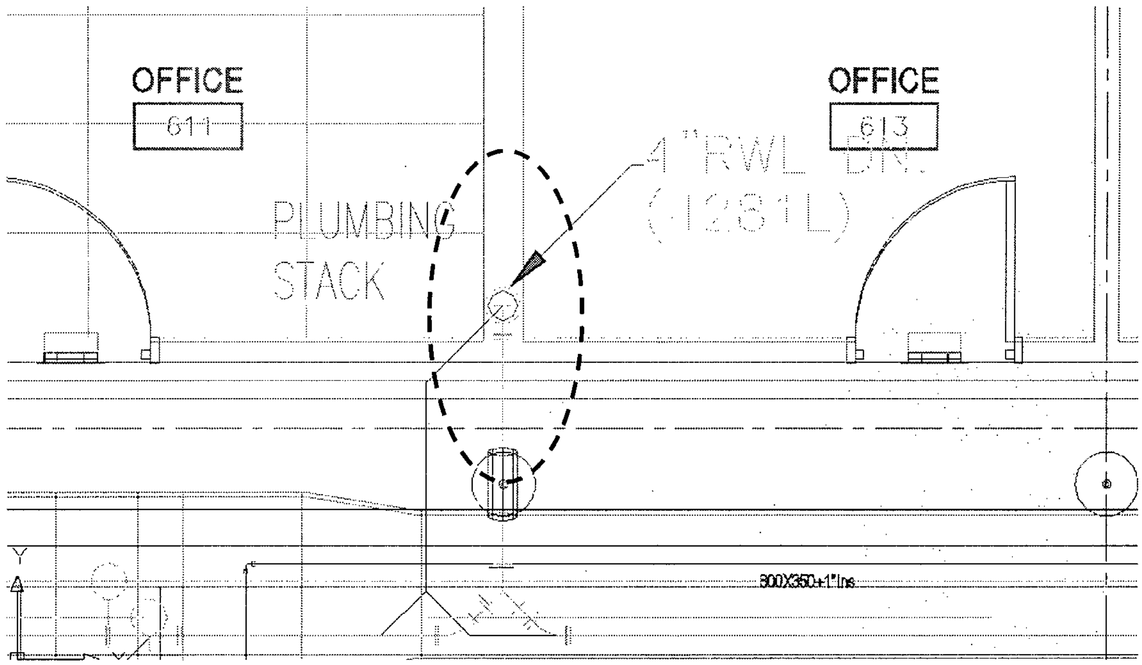


During the presentation, these points were raised and discussed:

- To save space, duct will run 2" below the slab, and follow the slope where applicable.
- The duct transition section from 1000x450 to 1000 x400 was changed from a top-flat to a bottom –flat, which saved us 100 mm in height (50 for the change in size, and 50 for changing the critical point to the lowest point of the slab).
- The Hot Water Supply & Return will run staggered to accommodate and minimize the necessary space in crossover height when branching.
- The HW S&R will run tight to the bottom of duct (after 2" clearance).
- The Rainstorm Water Drain was shifted so that it will not enter the office area before running down the floor. This will remove the elevation constraint imposed by the office ceiling height, restricting the RWD line to run below a certain elevation.

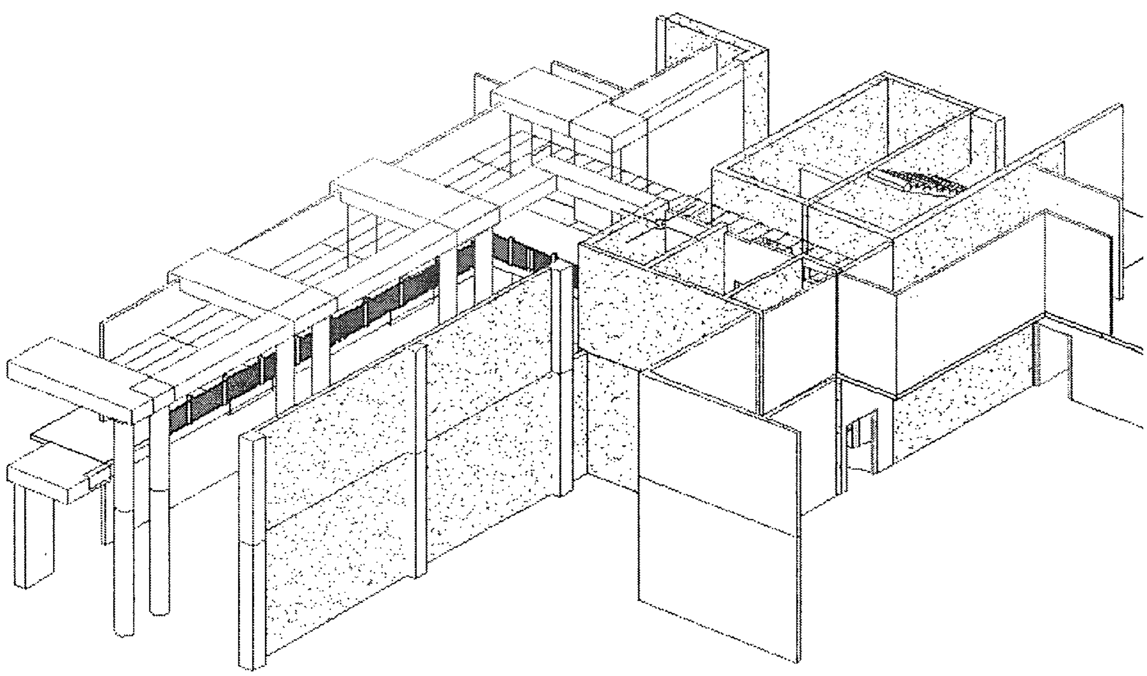
  The image below shows the layout of that storm rain drainpipe. You can see that it has changed from a 45-degree entrance to room 611 and now is going straight into the wall between the two offices.

  In addition, we should note here that this stack in the wall should be considered when calculating the thickness of this wall. This thickness will affect the layout of the curtain wall and windows, and perhaps it should be synchronized with other walls in this floor, in the same view.

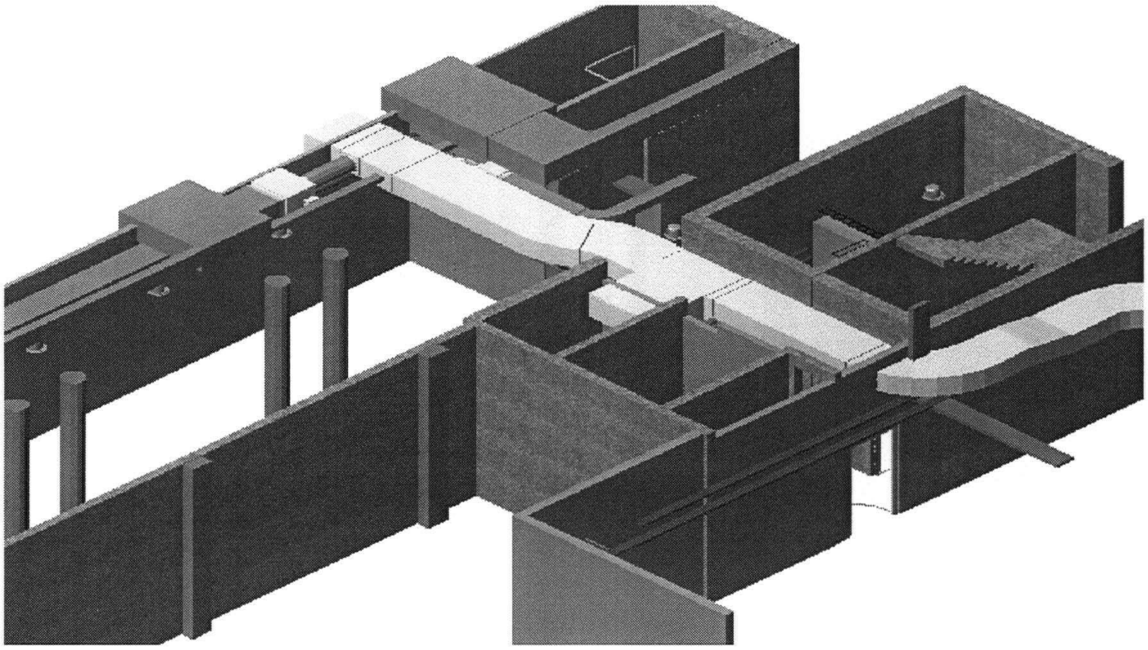


Main and 2nd Floors Corridor

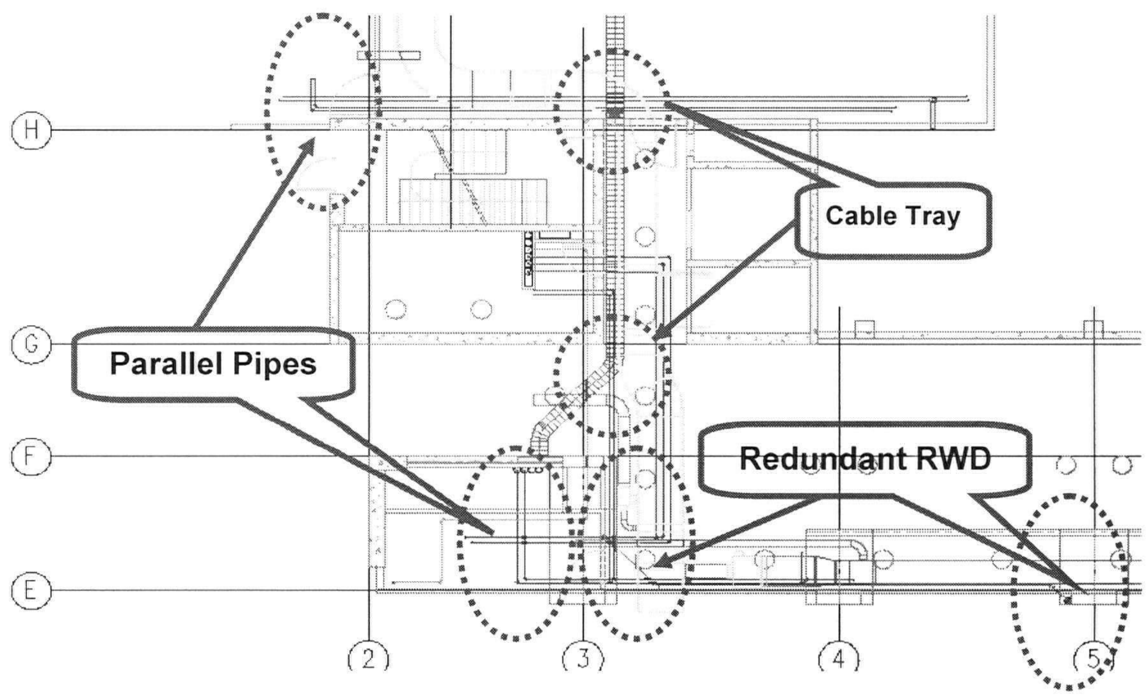
The second snapshot chosen for this exercise was the west core corridor around the Atrium and entering the "High-head Lab", on main and second floor.



Main Floor Corridor



The main floor major concerns and potential issues are illustrated in this plan.



The Rain–Storm Water Drain pipe

This pipe, which starts in the beam near grid 5 and goes all the way close to grid 3, seemed to be redundant. The reason was that in the lower floor, there is no stack near grids 3&E. Talking to the Plumbing sub, he mentioned that it could be reverse, but since the stack is continued in the basement near grid 5. But then again, there is nothing on the top floor close to 3&E to justify it. The consultant was notified and they may issue an omission soon.

The cable tray size and layout

The other main issue was the Cable Tray again. This time it was both the size and layout of it. The electrical sub mentioned that there is no need for a 450 mm wide cable tray anymore and later on, he mentioned that a 150 mm wide cable tray is enough for the services there.

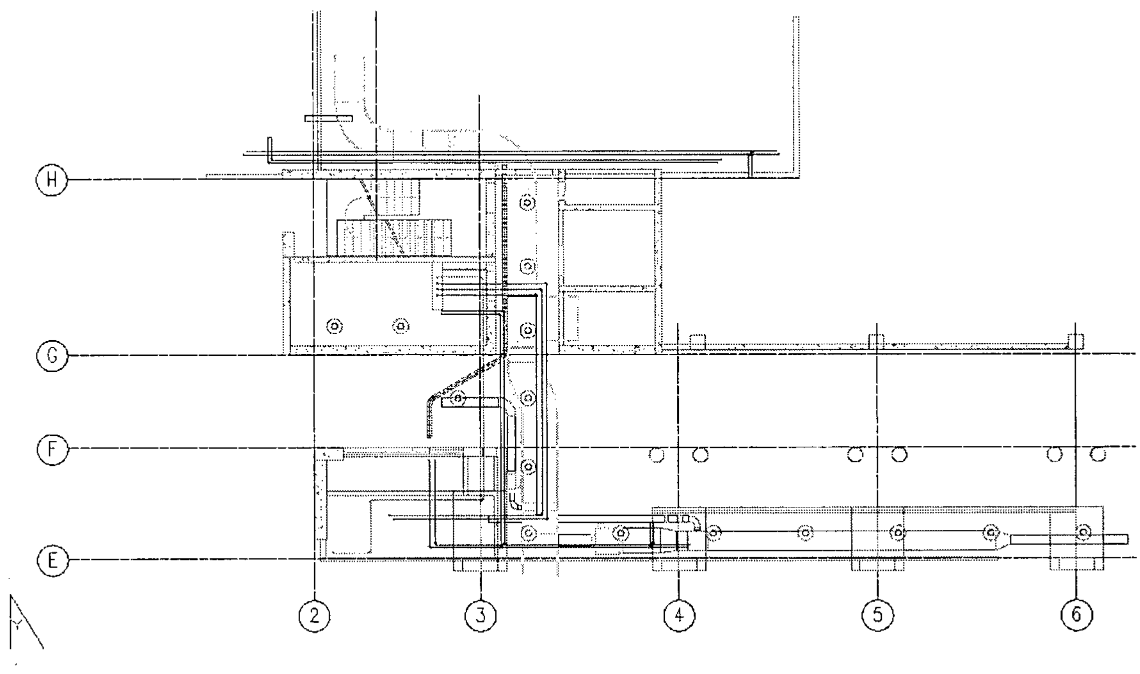
Nevertheless, the layout of this cable tray should be reconsidered as well. The first point to note is that the clearance for access is necessary. Furthermore, the three different ceiling elevations that it has to clear before reaching to the high-head lab corridor, should be considered .

The second point is, when it reaches that point to cross on top of the door 145A on Grid H, it should rise up to the second floor, which is going right through the ductwork. This means that either this layout should change, or the duct should shift to the east side of the corridor. Note that if the duct shifts to make room for the cable tray, it will block the way of the return-air grill.

Piping and Plumbing Layout

At this floor, the pipes running for HVAC system and plumbing systems are not many or complicated. Yet, due to the large size ducts and clearance needed for the cable tray, there is no room for error and they should be carefully executed to account for these constraints. In addition, there are some points that they need to cross over each other, which is shown in the first plan. Yet again, at the western entrance we face different ceiling heights that should be considered for the plumbing pipes elevation.

The next image is a plan with the proper layout of the systems to avoid some of the conflicts mentioned above.



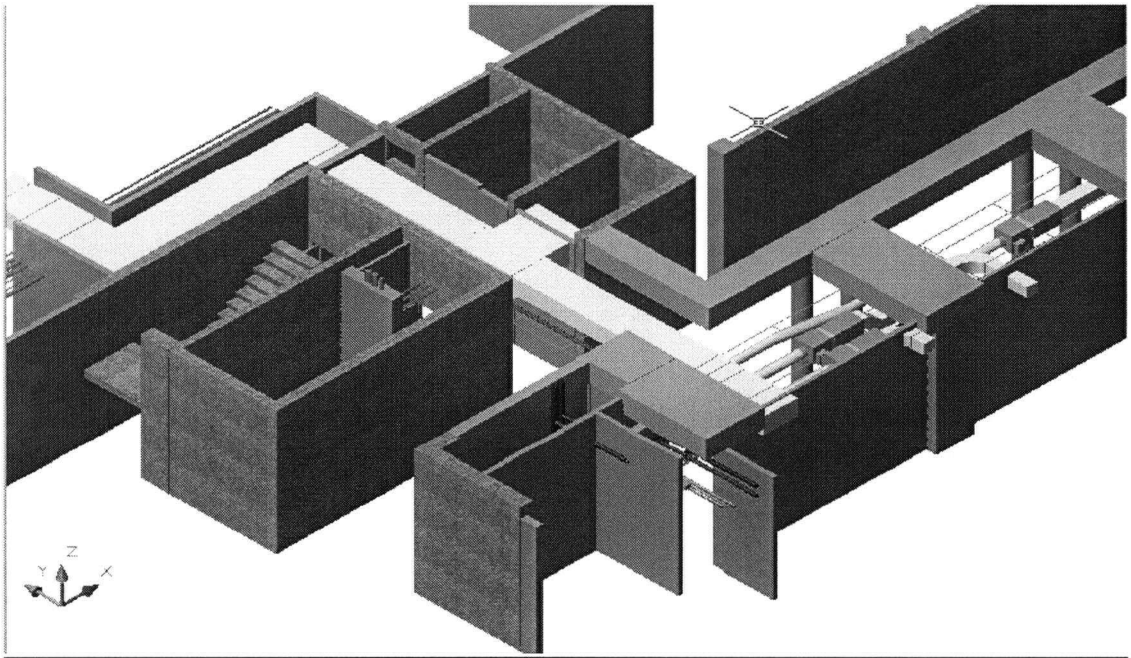
Other points to consider

The riser located in the washroom adjacent to the staircase, is a very busy area with lots of stacks going up through it. The drawings are not consistent in showing the order of these stacks, and that could be problematic (talking to the trades, it has already caused some).

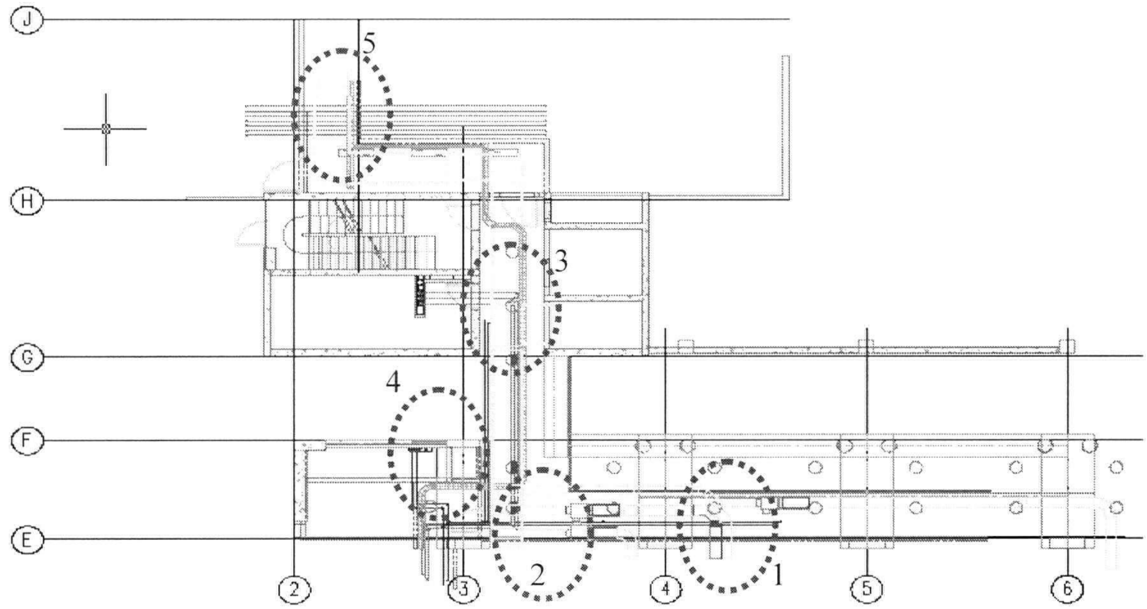
The Fire protection pipes are running exposed in the stair case area, which is all made of concrete. To this date, there is no detailed design on the fire protection pipes. Therefore if the location of pipes is not pinpointed before pouring the concretes, there will be considerable coring to be done later on.

2nd Floor Corridor

The 2nd floor and main floor had lots of similarities in terms of having a congested area in the ceiling space above corridors, and having large size ducts and the same plumbing elements. Also the concerns noted above regarding the washroom and staircase, applies to the 2nd floor as well.



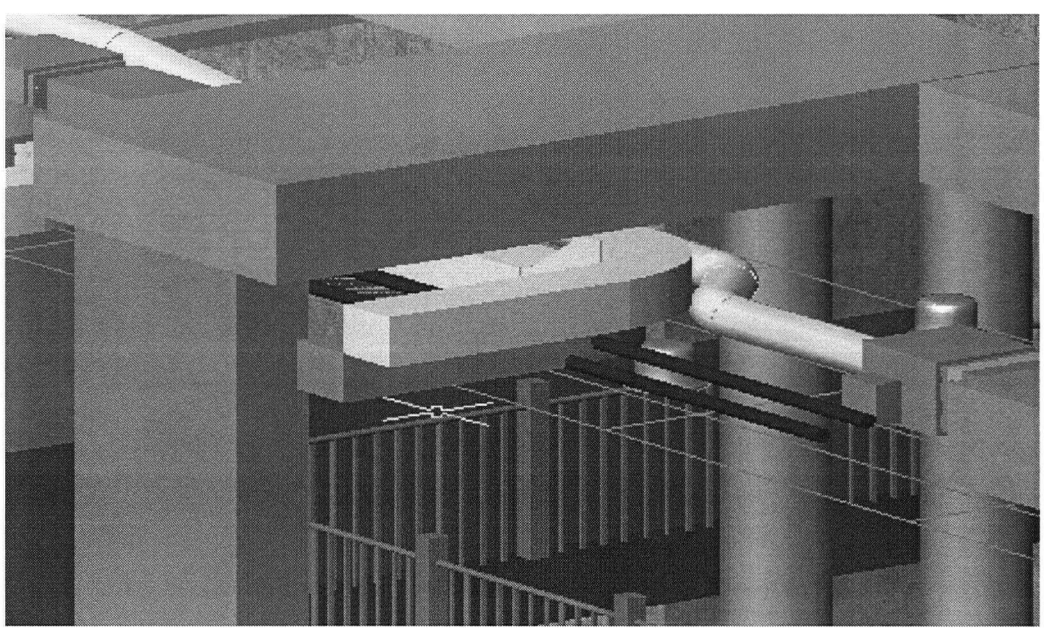
The main points to consider in this floor are shown in the following plan:



Ductwork offsets

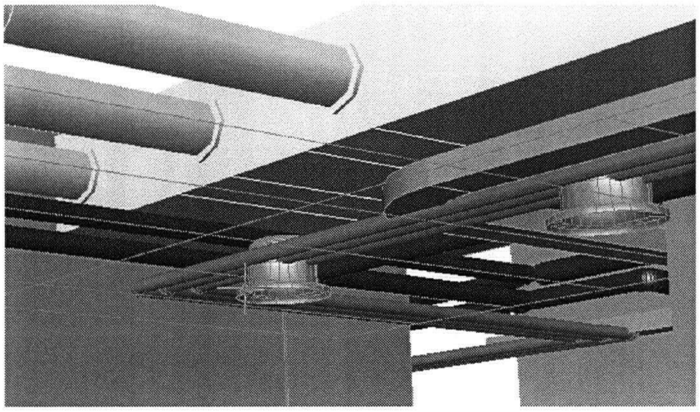
When supply ducts are trying to reach the areas south of grid E, there is a necessary rise due to the rise of the ceiling height. At the highlighted point [#1] near gridlines E & 4+ when applying the offsets in the way indicated in the drawings, the duct and HWS&R pipes run into each other. This could be avoided by offsetting the duct before the elbow.

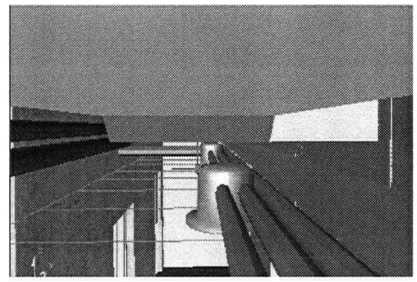
The potential problem and the solution to it is shown in the next picture (the darker duct shows the problematic position, and the lighter duct is the solution)



Congested areas to notice, and the plumbing pipes

The other two marked areas in the floor plan, between grid 3 and 4, are the location of congested areas to consider. As we can see in the images below, current schematic layouts will result in interference of plumbing pipes with the cable tray and the lighting fixtures.





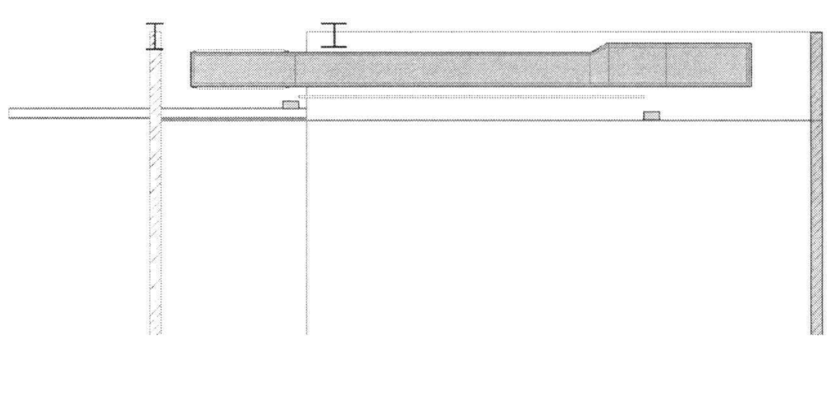
The picture on the left is close to Grid E [#2], while the picture on the right shows the ceiling space close to grid G [#3].

Slab opening and trimming the concrete beam

Another point discussed while building the model, was the fact that in the structural drawings, the beam along grid 3 was trimmed near grid F to provide more space in the opening riser adjacent to it. However, in the architectural drawing (slab edge drawings) the beam was not trimmed and the opening was smaller.
Although the Architect stated that the architectural drawing overrides other drawings, I believe that the necessary opening size should be double-checked before the final decision.

The cable tray clearance in the corridor of High-head Lab

This issue was raised in the meeting by architect and was discussed. The main reason behind the discussion was the elevation of the steel structural beams (I-beams) located there (marked near Grids H and 2+) that would force the duct and therefore everything else to shift to a lower elevation which would invade the access clearance space necessary for the cable tray. (Section along H+, looking north)



Later evaluation of the drawings illustrated a conflict between elevation codes of high-head lab structure in the architectural and structural drawings. In addition, the architectural drawings with the correct elevation were not accounting for the roof slope in that area. Fortunately, the results showed that we have more space available at that point than anticipated earlier and therefore less worries.

Fire protection issue

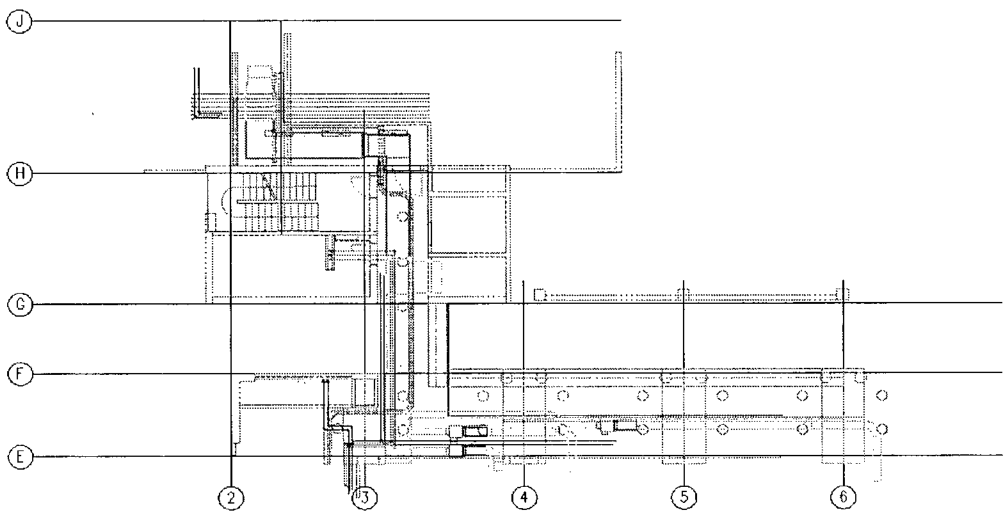
With all that said, the fire protection can turn everything upside down in the results of this model at this floor. The design information available at the moment is not enough to implement the system in the model. Nevertheless, in the main west-core corridor, we know we have double-headed sprinklers which puts lots of constrains in this already-congested area.

Also, in the high-head lab corridor, the wall-mounted sprinkler line is added to the ceiling-mounted line, and makes it necessary to re-evaluate the whole model in this area once the fire protection design is complete. Currently, we know that there will be interference between conduits and these sprinkler lines along the wall of the corridor near grid (H+).

Plumbing Pipes

At the north side of the model (Marker #5 near Grids H+ and 2+) a large number of plumbing pipes will have to cross the corridor. Although it was not within the scope of this model, it was illustrated to bring up the issue for future consideration. At the moment, this is an unresolved interference, between these pipes and the rest of the elements running within the corridor space.

The space below the duct can provide a tight space to cross these pipes below the duct, but the fire protection pipes might change this situation. Alternatively, there is enough room above the duct to cross these pipes but we have to penetrate the steal beam and that can be done but has some restrictions. In addition, the slope of the roof deck should also be considered, since this corridor is located at the highest point of the roof deck. Here is the snapshot of the proper layout of the systems in the 2nd floor to avoid some of the conflicts mentioned.



Note that the pipe-sizes in the plumbing drawings (P103) for this area are missing.