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Design and Diagnostic Problem-solving Approaches – Application to Thermal Comfort and Indoor Air Quality

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Dr. Ahmed Cherif Megri, Associate Professor of Architectural Engineering (AE). He teaches capstone, lighting, electrical, HVAC and energy design courses. He is the ABET Coordinator for the AE Program. His research areas include airflow modeling, zonal modeling, energy modeling, and artificial intelligence modeling using the support vector machine learning approach. Dr. Megri holds a PhD degree from INSA at Lyon (France) in the area of Thermal Engineering and "Habilitation" (HDR) degree from Pierre and Marie Curie University - Paris VI, Sorbonne Universities (2011) in the area of Engineering Sciences. Prior to his actual position, he was an Associate Professor at University of Wyoming (UW) and prior to that he was an Assistant Professor and the Director of the AE Program at Illinois Institute of Technology (IIT). He participated significantly to the development of the current architectural engineering undergraduate and master's programs at IIT. During his stay at IIT, he taught thermal and fluids engineering (thermodynamics, heat transfer, and fluid mechanics), building sciences, physical performance of buildings, building enclosure, as well as design courses, such as HVAC, energy, plumbing, fire protection and lighting. Also, he supervises many courses in the frame of interprofessional projects (IPRO) program.

Areas of Interests: - Zonal modeling approach, - Integration zonal models/building energy simulation models, - Zero Net Energy (ZNE) building, - Airflow in Multizone Buildings & Smoke Control, - Thermal Comfort & Indoor Air Quality, - Predictive modeling and forecasting: Support Vector Machine (SVM) tools, - Energy, HVAC, Plumbing & Fire Protection Systems Design, - Computational Fluid Dynamic (CFD) Application in Building, - BIM & REVIT: application to Architecture and Electrical/Lighting Design systems.

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Abstract:

The engineers are usually confronted to two types of problems: design or troubleshooting. The design concerns the creation of a new product (in our case the product is a building, building component, mechanical or electrical system) and the troubleshooting involves fixing an existing product using a sequential diagnostic.

In this paper, we introduce how these two notions have been introduced to undergraduate students through an undergraduate design course. Two case studies from building engineering are presented: thermal comfort and indoor air quality (sick building syndrome) taken from undergraduate design courses. A flow chart is presented and discussed for both cases.

We discuss the design program from students' point of view, and the experience earned in design, experimentation, and also in written and oral communication skills. Future plans to evaluate the effectiveness of the case studies in terms of learning outcomes, as well as plans to evaluate it in undergraduate architectural engineering training are also presented.

1. Introduction:

Teaching a design course is challenging and differentiates from fundamental courses at different levels. The fundamental courses are based on specific laws (first law of thermodynamics, heat transfer equation, radiosity technique, and so on). The textbooks usually include a large number of examples for each topic, where students use as references to solve their home works and exams, through memorization, understanding and application. Design courses need more analysis and evaluation, since the problems are open-ended and usually the step-by-step process is not clearly identified in the textbooks and lectures. As well, the textbooks are not numerous and the examples within the textbooks are not abundant. Undergraduate students taking a design course for the first time have the tendency to focus on details and miss the big picture and the understanding of the objectives of the design problem.

It is important to explain to undergraduate students the difference between design and diagnostic, where the design concerns a new product that need to be produced, respecting certain rules, standards and codes. The codes and standards are there to make such product sustainable, safe, economic and respecting the environment.

The diagnostic in the other hand focuses more on the understanding of an existing product or a situation and try to correct the malfunctioning of the whole system or only a part of it. In this case, the product is already there and our job is to identify the problem (s) and come up with the appropriate solution (s). To do so, we need to use tools and equipment to measure and identify the parameters that help us to identify the problem (s). This kind of work needs expertise and understanding of how to measure and identify the fundamental parameters, such as temperature, pressure, concentration, illuminance, and airflow.

Design and troubleshooting are considered as two subcategories of problem solving (McCade). Problem solving has been defined in many ways. Ritz describes a problem as a need which must be met (Ritz, et al. 1986a). The main difference between the two subcategories is the fact that the design is a "proactive" problem solving (Baker & Dugger, 1986) and the troubleshooting is a "reactive" problem solving (Baker & Dugger, 1986). The design involves more innovation, where the troubleshooting involves the recognition that technology encompasses (Baker & Dugger, 1986).

More recently, Design is defined by Nielsen (2003), *"A Problem is basically impression of a tension or a contrast between two conditions: Condition of Desires and Actual Condition"*. The successful design of an item transforms a condition of "Desire" (or need) into one of "Actuality". These definitions are supported by Jonassen (2004) when he writes *"First, a problem is an unknown entity in some context"*, and *"Second, finding or solving for the unknown must have some social, cultural or intellectual value*". He then adds one vital ingredient, *"someone believes that it is worth finding the unknown"*. Jonassen (2004) in his book has focused on the following three types of problems: story problems, troubleshooting problems, and case and system and policy analysis problems.

A problem-solving method describes a reasoning process that efficiently achieves a goal by applying domain knowledge. Nickols (2012) states that choosing the right problem solving approach makes a difference. He identifies three different problem solving tasks: repair, improve, and engineer. Stojcevski (2005) mentions that problem solving is a special kind of skill to learn. Benjamins et al. (1995), states that a problem-solving method cannot directly be applied because of the existence of a gap between, on the one hand, a problem-solving method and the domain knowledge it uses, and, on the other hand, a problem-solving method and the goal that it is supposed to achieve. He distinguished two types of assumptions that are able to bridge the gap: one type of assumption is used to strengthen a problem-solving method, and the other to weaken the goal to be achieved.

In this paper, we introduce how these two notions have been introduced to undergraduate students through basic design course. Two case studies from building engineering are presented: thermal comfort and indoor air quality (sick building syndrome). These two case studies have been taken from basic design courses. A flowchart is presented and discussed for both cases.

We discuss the design program from students' point of view, and the experience earned in design, experimentation, and also in written and oral communication skills. Future plans to evaluate the effectiveness of the case studies in terms of learning outcomes, as well as plans to evaluate it in undergraduate architectural engineering training are also presented.

2. Design problems:

The design problem concerns the creation of a new product (in our case the product is a building or one of its components, mechanical or electrical systems). In this case, the designer needs to respect multiple standards and codes, such as ICC codes, NEC code, ASHRAE 55-2010, ASHRAE 62-2010, and ASHRAE 90.1-2013.

2.1.Thermal comfort:

The thermal comfort model Fanger's PMV-PPD model (Fanger, 1970) used for ASHRAE 55-2010 (ASHRAE, 2010) is considered in this study. Using this model, the occupant is regarded as a non-participating, passive recipient of the thermal stimuli offered by their environment, with the latter being assessed subjectively against very specific expectations of what such an environment should be like. Engineers seem to be inclined towards the deterministic research outputs embodied in models such as PMV-PPD, presumably because it fits with their view of the role of HVAC in indoor air.

The human body has a complex regulating system acting to maintain the deep body temperature regardless of the environmental conditions. A heat balance that involves metabolism, blood circulation near the surface of the skin, respiration, and heat and mass transfer from the skin, essentially controls human body temperatures. Comfort involves control of temperature, humidity, air motion, and radiant sources interacting with the occupants. The ASHRAE Standard 62-2010, « Ventilation for Acceptable Indoor Air Quality » provides procedures for achieving acceptable indoor air quality, while the standard 55 « Thermal Environmental Conditions for Human Occupancy » provides procedures for achieving acceptable thermal comfort conditions.

Many indices have been developed to simplify description of the thermal environment and to take into account the combined effects of two or more of the environmental factors controlling human comfort, such as ET*, SET, TSENS, and so one.

The most comprehensive indices are the PMV and PPD, since they include more environmental and physical parameters: air temperature, humidity, air movement, and thermal radiation, as well as clothing and metabolism.

The PMV is the predicted mean vote of a large group of people exposed to the thermal conditions of interest and providing a rating on the following scale: +3 Hot, +2 Warm, +1 Slightly Warm, 0 Neutral, -1 Slightly Cool, - 2 Cool, and -3 Cold. PMV is derived based on a total energy balance on subject combined with an empirical fit to thermal sensation vote. PMV establishes a thermal strain based on steady-state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain. The predicted percentage dissatisfied (PPD) is related to the PMV and is based upon the individual variation in response for a given set of conditions. A value of PMV = 0 is neutral and said to provide comfort conditions with an associated PPD of 5%. A PMV = +1 or -1 provides a PPD of around 25% and so on. The couple PMV / PPD is calculated from the knowledge of the six basic physical factors: air temperature, mean radiant temperature, relative humidity, air velocity, metabolism (activity level) and clothing value (Fanger, 1970).

In the design process, the thermal comfort is evaluated in association with energy simulation, where the outdoor conditions are taken from the weather data, and the indoor conditions are predicted using energy simulation programs, such as Energy Plus, eQUEST, TRNSYS. Consequently, the thermal comfort indices are predicted and the thermal comfort is evaluated in different location of the building, using PMV and PPD indices.

2.2.Indoor Air Quality:

The indoor air quality is a large subject that necessitates a deep understanding. ASHRAE Standard 62-2010, “Ventilation for Acceptable Indoor Air Quality”, defines acceptable indoor air quality (IAQ). HVAC systems, in addition to maintaining thermal comfort, must also provide a clean healthy, and odor-free indoor environment.

The term "sick building syndrome" (SBS) is used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. The complaints may be localized in a particular room or zone, or may be widespread throughout the building. In contrast, the term "building related illness" (BRI) is used when symptoms of diagnosable illness are identified and can be attributed directly to airborne building contaminants (EPA, 2001).

Sick Building Syndrome is a general category for a number of ailments, allergies, and complaints, all due to some physical aspect of a building, usually related to the ventilation system. The existence of low levels of pollutants, synthetic irritants, fungi or other microorganisms, or simply a lack of adequate fresh air, are sufficient factors to cause reactions in a percentage of building occupants. In 1997, it has been discovered that the slimy black mold has proven deadly in three Oakland County homes (R. Mishra, 1997). The sick building syndrome is a very serious problem, since we construct more and more tight building for energy-saving measures, chemical pollutants are not diluted and are continually recirculated throughout the building. Despite numerous investigations, journal articles and conferences, little has actually been proven about the causes of sick building syndrome. The causes are multiple and sometimes very difficult to detect. The only common denominator of Sick Building Syndrome is insufficient ventilation air to remove the contaminants. Inadequate ventilation has been considered to be a causal factor in 50 % of sick buildings in the United States and in 68 % of Canadian investigations (Melius 1984; Collet and Sterling 1988). Sometimes the source of the problem is microbial growth inside wet ductwork or other air-handling equipment. Air-conditioning systems themselves can harbor pollutants and micro-organisms and so add to the contamination of the building. In some new buildings the problem can be the use of synthetic materials (such as insulation or carpeting) which release hydrocarbons or other vapors into the air at a very low rate. In rare instances the outside air intakes may draw in foul air from waste storage or processing areas, or from parking areas heavily laden with auto exhaust. These cases represent bad ventilation system design.

In the design process, the indoor air quality may be evaluated in association with airflow prediction using simulation programs, such as CONTAM and COMIS, where the outdoor conditions are taken from the weather data, and the indoor conditions such as concentration of several contaminants are predicted.

3. Troubleshooting problems:

The troubleshooting consists of fixing an existing product using a sequential diagnostic. It is a logical, systematic search for the source of a problem so that it can be solved, and so the product or process can be made operational again. Troubleshooting is needed to develop and maintain complex systems where the symptoms of a problem can have many possible causes.

3.1.Two case studies

Two case studies will be discussed. In the first case, a methodology is developed to evaluate a discomfort situation. In the second case, a sick building syndrome situation is studied and an expert system is developed, based on mold investigation and multizone airflow simulation, to predict the reasons of such problem.

3.1.1. Thermal Comfort

A multzone building is considered for this study. The objective is to study the thermal comfort of such existing building. This study is completed with a parametric study, to identify the comfort and discomfort zones in different thermal conditions.

- Identification of the geometry, window locations,
- Identification of specific locations where the thermal comfort is a concern
- Measurement of temperature, air velocity, and relative humidity
- Calculation of the Mean Radiant Temperature (MRT)
- Estimation of the clothing (CLO) and the activity (MET)
- Indices: Estimation of the PMV and PPD
- Check if the thermal comfort is verified using the ASHRE 55-2010
- Correction of the problem using a multiple parametric study (Figures 2 and 3 as example).

The flowchart for such work is represented on the figure 1.

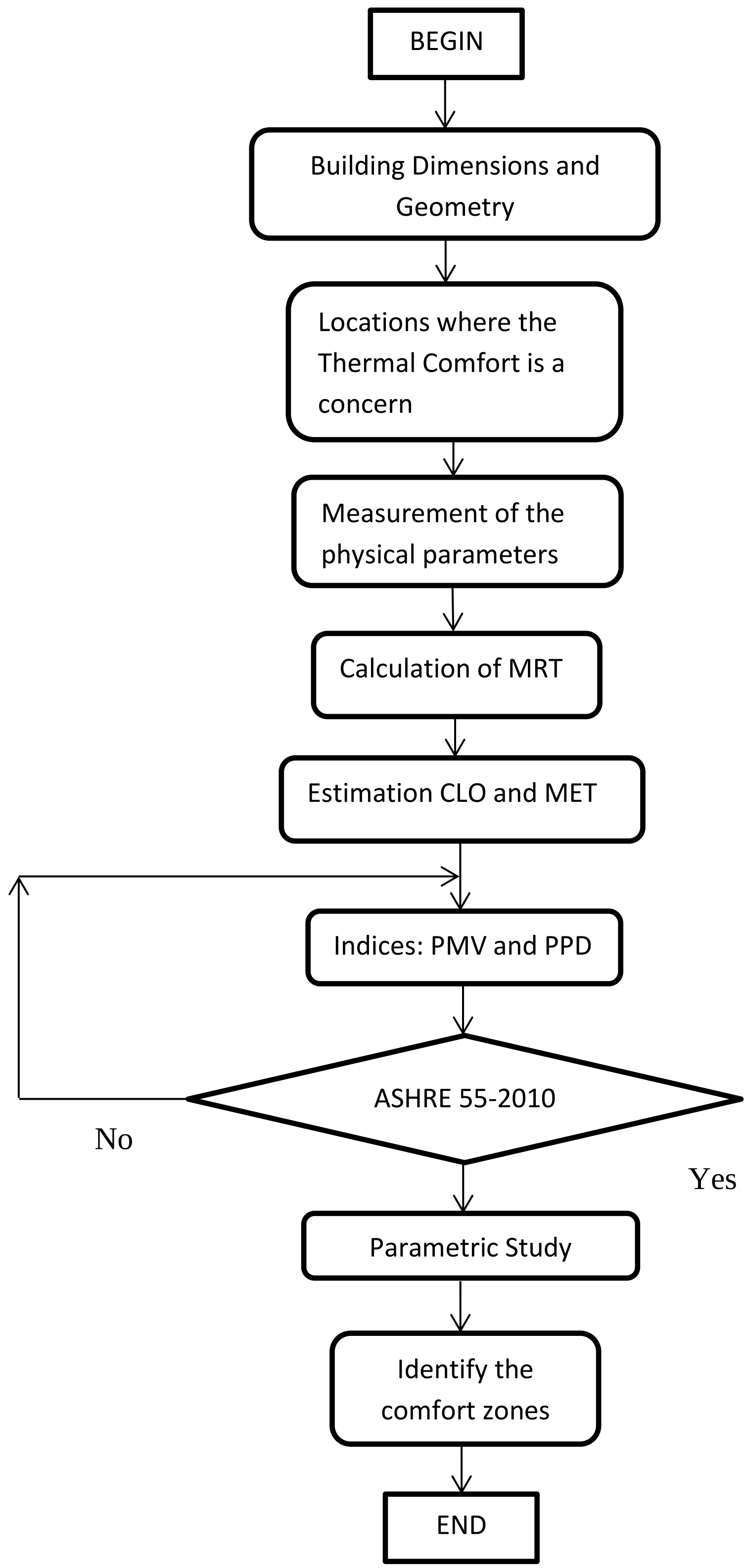

Figure 1: flowchart of the procedure developed for diagnostic thermal comfort

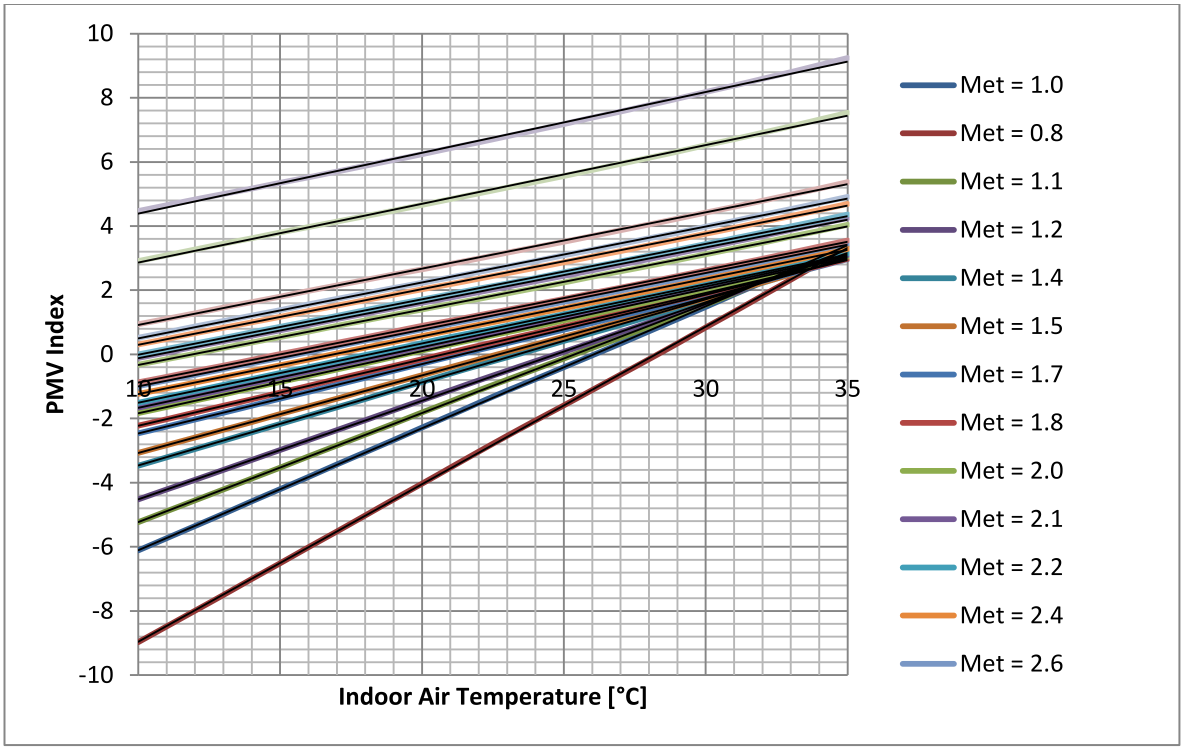

Figure 2: PMV Index vs. the indoor air temperature and the activity (MET)

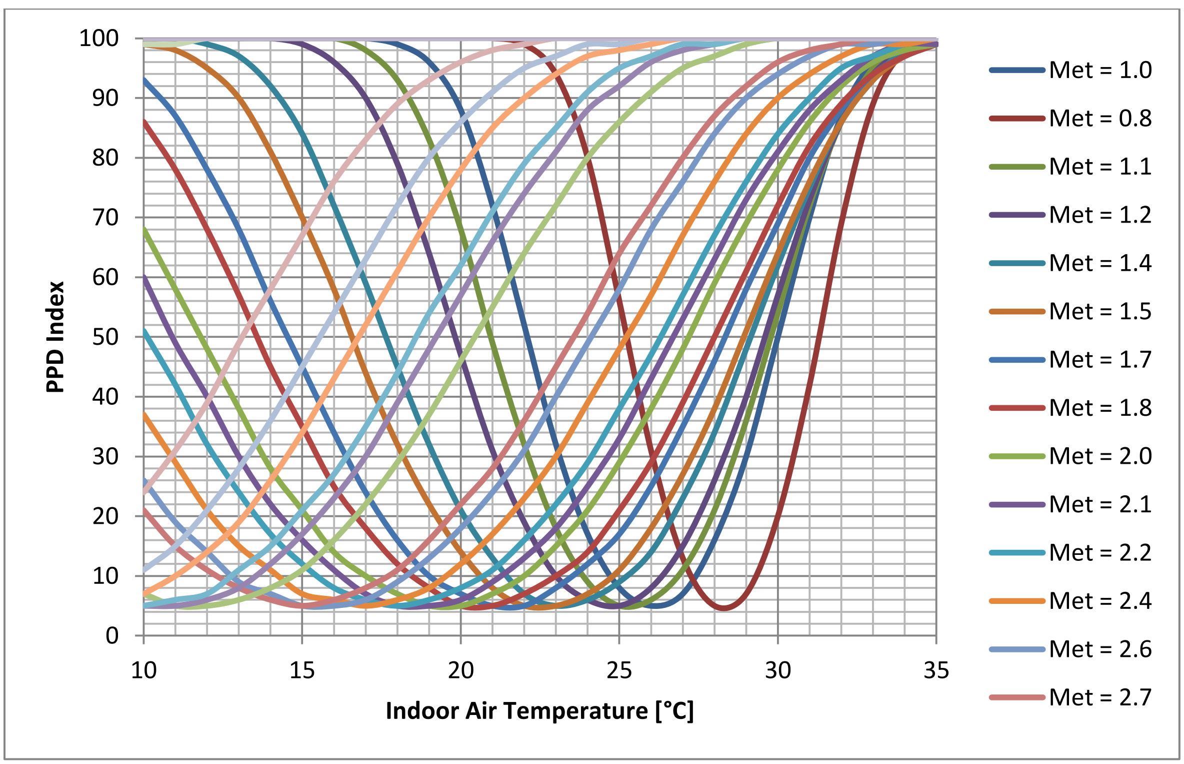

Figure 3: PPD Index vs. the indoor air temperature and the activity (MET)

3.1.2. Indoor Air Quality and Sick Building Syndrome:

Major activities and tasks:

- Understanding the sick building syndrome (Why good indoor air quality is important? What causes Sick Building Syndrome? The effect of poor indoor air quality on the life and health of people),
- Literature revue to obtain rules and solution for each specific problem (new and retrofit buildings),
- A methodology technique to diagnose a sick building:
- each group of students analyze a sick building in the area of Chicago,
- Use computer software to determine the level of indoor air quality in the building and how to improve it.
- Expert System (Figure 4) to help the designer to integrate the sick building syndrome in the building design: A number of rules should be developed to integrate expertise from different professional concerned with indoor air quality and sick building syndrome, using a questionnaire and face-to-face interviews. The sick building syndrome is a multidisciplinary problem since the causes of sick building syndrome are multiple, such as, contamination (inside and outside), material used to construct the building (formaldehyde, fiberglass), inadequate ventilation, hypersensitivity pneumonitis, cigarette smoking, humidity, noise and illumination, scabies, and other unknown syndrome. An interprofessional experience in different fields such as HVAC systems, Indoor air quality, Biology and medicine (allergies, molds, and fungi), Maintenance, Building Science, Building Materials, and environmental engineering is needed.

4. Survey and course evaluation:

The authors believe that the two subcategories of problem solving: Design and troubleshooting are misunderstood by the students and it is very important that the design course instructors need to be contacted and their voice be heard with regard to incorporating the topic of troubleshooting in teaching and learning Design. At the first level, a survey instrument that addresses two aspects of teaching engineering Design: the importance of the two subcategories, and the importance of the incorporation of these two subcategories in teaching engineering Design. We conduct this survey before and after the course during two consecutive years and the results are very similar.

The survey questions are:

Question 1: Do you understand the importance of "Design" for engineering education? (Not at all Important, Very Unimportant, Neither Important or Unimportant, Very Important, Extremely Important)

Question 2: Do you understand the importance of “Troubleshooting” in engineering education? (Not at all Important, Very Unimportant, Neither Important or Unimportant, Very Important, Extremely Important)

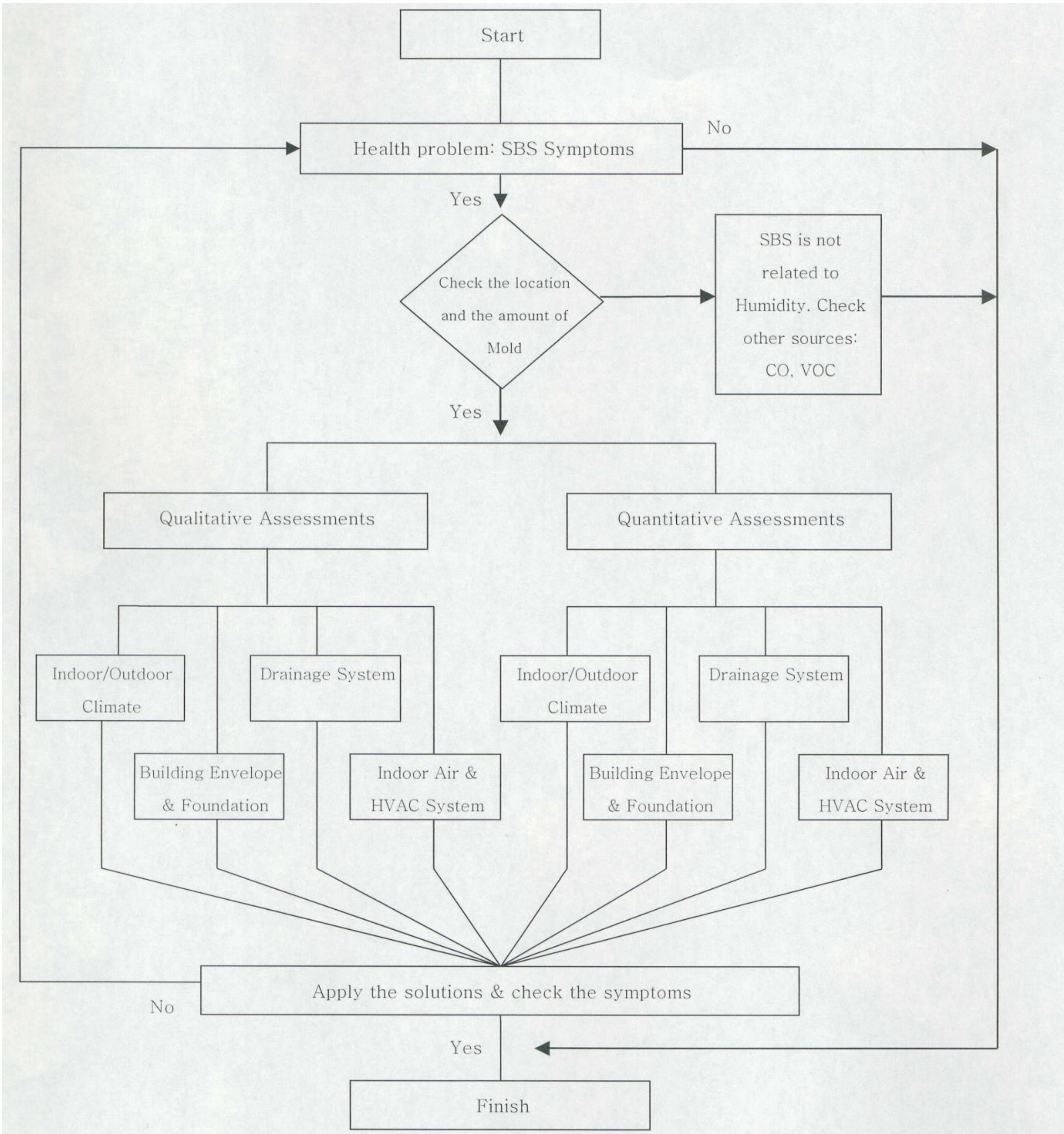

Figure 4: The Expert System developed to predict the SBS within buildings

Question 3: Do you understand the difference between design and troubleshooting? (Much Lower, Lower, Average, Higher, and Much Higher)

Question 4: Do you think it is important to incorporate the topic of "troubleshooting" in Design Courses? (Not at all Important, Very Unimportant, Neither Important or Unimportant, Very Important, Extremely Important)

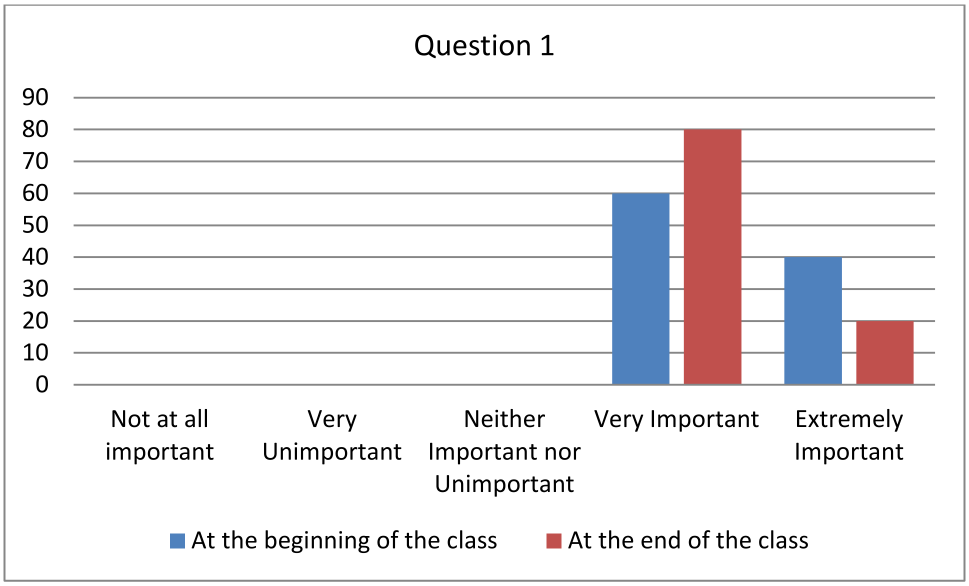

Figure 5: Question 1: Do you understand the importance of "Design" for engineering education?

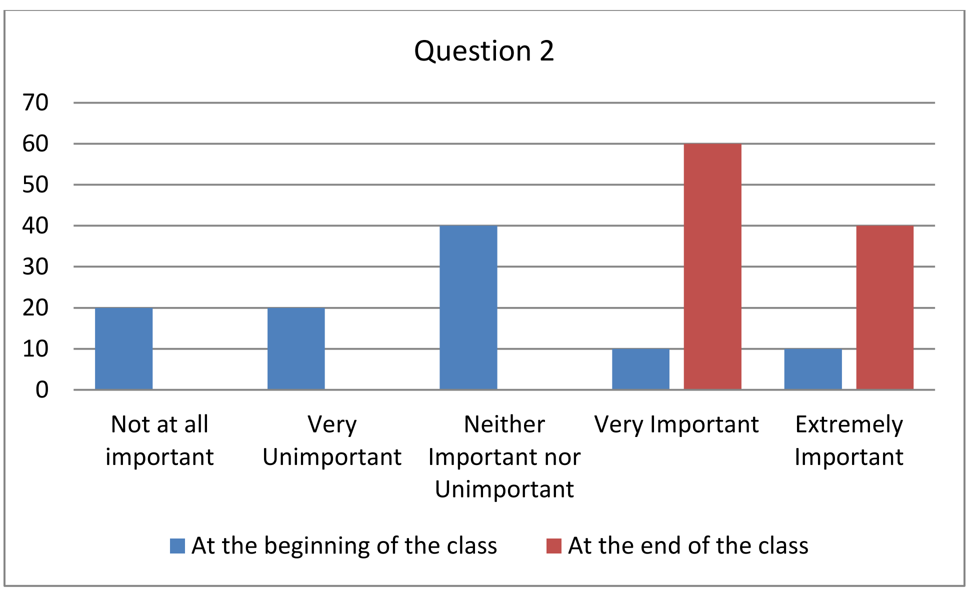

Figure 6: Do you understand the importance of "Troubleshooting" in engineering education?

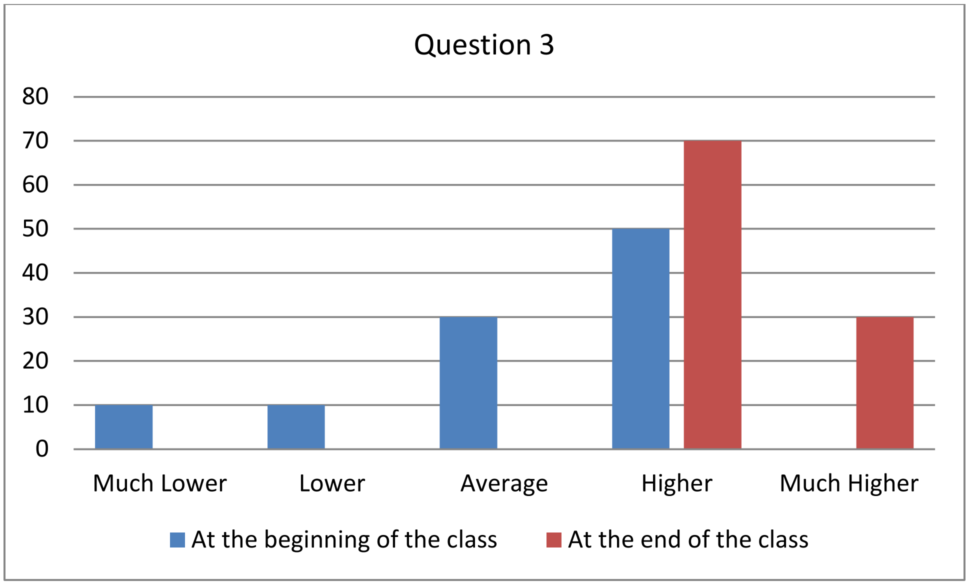

Figure 7: Do you understand the difference between design and troubleshooting?

Here, responses of design students to Questions 1, 2, and 3 are summarized (Figures 5 to 7). Based on the responses to Question 1, where the importance of design is similarly recognized at the beginning and the end of the semester, the respondents change their mind, regarding the importance of the teaching of troubleshooting within design courses. Regarding the Question 3 survey, we notice a progress in term of understanding of the difference between two aspects of problem solving: design and troubleshooting (Figure 7).

In parallel with the self-evaluation of each course by the instructor, we also conduct a course evaluation by students. The course objectives introduced earlier in the course are again provided to the students at the end of the semester. The students' input on whether the materials offered have met the objectives is then complied and used in the program outcome assessment process. Results of instructor course evaluations (conducted by students) are reviewed by the Department Chair and the Dean and shared with the faculty.

Each faculty member also conducts an evaluation of performance of students in his/her courses as part of the Program objectives and outcome assessment process. A summary report on the performance of students (to meet the Program objectives) and compliance with the Program outcomes is prepared and submitted to the Department Chair for the assessment purposes.

Future plans to evaluate the effectiveness of the capstone in term of learning outcomes: Actions that will be implemented to improve the effectiveness of the curriculum in term of learning outcomes:

- We expanded on the instructors' self-evaluation such that more direct assessment of students' learning outcomes is obtained. A set of standards for instructor's self-evaluation will be prepared by the faculty and the Board of Advisors and will be implemented with the annual assessment cycle. The main point of these standards is that the evaluation of students' performance will based on samples of work in three categories of students: those in the upper 75 percentile, those in the 50 – 75 percentile and those below the 50 percentile populations. Thus the assessment results compiled are based on course performances and grades, exams, projects, presentations of students, and writings as required in some courses. Furthermore, each course specifically addresses the learning outcomes and relation between the course and the Program outcomes, the methods used for the evaluation of students' performance and the relevance of the course materials to the Program outcomes following the standards adopted for the assessment process.

- Students will be provided with the course descriptions including learning objectives and outcomes. Students also will provide their input on the Program outcomes. The results from this instrument are used along with those from the instructors' self-assessment of courses as a means to ensuring compatibility in results obtained.
- A more rigorous process in assessing the learning outcomes of this capstone course will be implemented, which are in parallel with the Program outcomes. The following outlines process will be used for this capstone course assessment.
    - Individual instructor evaluation of the degree of learning achievement of individual students on a capstone team, which includes consideration of the collective achievements of the team.
    - Peer evaluation (optional by instructor).
    - Grading of deliverables by the instructors (project plan, mid-term review, final report, exhibit (and abstract), oral presentation, team minutes, web site if applicable).
    - Teamwork survey.
    - Self-assessment.
    - Senior Design Symposium judging (with evaluation criteria explicitly indexed to the learning objectives and articulated via rubrics for all measures).

5. Conclusions:

Teaching a design courses for undergraduate students is challenging and require real applications, where students need to perform experimental, as well as simulation works to analyze the system under consideration. The main objective is to familiarize them with the two approaches that usually will confront in their future.

The two approaches are design a new product (building, mechanical and electrical system) or diagnose an existing system, because of a dysfunction in term of performance (discomfort, sick building syndrome, and so on). The approaches are developed and tested through case studies. The case studies may concern thermal comfort, indoor air quality, building illumination, and other issues encountered in modern residential and commercial buildings.

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