

# STUDY AND PRACTICE ON HVAC SYSTEM COMMISSIONING

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**ABSTRACT:** HVAC commissioning has come to be recognized as most important process needed for design, construction and operation and maintenance of HVAC system to realize owners true project intent and establish energy saving and sustainable operation and management of the building system. The author first introduce basic concept of commissioning and its actual procedure to be executed at each phase of building project, introduces brief history on the progress of commissioning concept and discusses differences among similar processes, and then introduces the author's experience of initial commissioning project to show actual procedures of commissioning process. Among tools expected to well perform each style of commissioning business, system simulation program will be useful for design commissioning, post acceptance commissioning and continuous commissioning. Five typical programs are compared about their functions and energy calculation results in order to verify availability of system simulation programs as a commissioning tool.

*Keywords:* HVAC, system simulation, commissioning, comparative study

## 1. WHAT IS COMMISSIONING (PROCESS)?

We can not find the word "commissioning" in English dictionary, so that it is considered as the gerund of "commission" in which we find the meaning "put a warship on duty" likely as an origin of commissioning concept, as popularly said. In this sense commissioning focuses on the inspection at hand over/acceptance of the building and systems. Building and/or HVAC commissioning in nowadays sense, however, is understood as the process to realize the real owner's project requirements through building construction stage and continuing to operation and maintenance stage as the life-cycle process in an ideal sense, by defining owner's project requirements, or OPR, on performance, reviewing, inspecting, verifying and testing a total functional performance. That is, commissioning just at the acceptance step is too late and remains quite insufficient, if not initiated at the program phase, and continuous commissioning after acceptance is also necessary to optimize system operation and detect faults and diagnose them. Thus, the commissioning should have the view for lifecycle of the building and systems and this kind of commissioning as a system will be well imagined by using the term "commissioning process" and well discriminated from the terms inspection, receiving, acceptance, verification, etc. as the incident at a certain point.

### 1.1 How commissioning is defined?

Commissioning, Cx: Commissioning is to diagnose and verify building system performance, and to propose ways to improve the performance in compliance with owner's or occupants' requests, necessarily accompanied with fully developed documentation. Commissioning is performed in order to keep the system in optimal condition through the life of the building from the viewpoints of environment, energy and facility usage. These viewpoints include energy conservation, indoor air quality, urban and global environment, maintainability and preventive maintenance of building systems.

The commissioning is carried out under the instruction of a qualified commissioning authority, to ensure that building system is designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with design intent or users requests. Commissioning begins with pre-design phase and can be applied through the life of a building including all phases, which are pre-design, design, elaboration, construction and operation and occupancy phases.

Commissioning Process, CxP: Commissioning Process is defined as a process from production stage to operation and maintenance stage for the purpose of accomplishing the commissioning aim. The two stages are divided into five phases: 1) pre-design, 2) design, 3) elaboration 4) construction, and 5) operation and occupancy. The phases are subdivided into eight steps: 1) program, 2) planning, 3) preliminary design, 4) working design, 5) elaboration 6) construction, 7) acceptance, 8) post-acceptance, and, 8) ordinary operation steps. At the milestones between these steps, there are contracts between owner and commissioning authority, design professional and contractor, the acceptance of the building system, and submission of the final commissioning report, etc. The range of the commissioning process to be im-

plemented depends on the wishes of the building owners and can be defined in a contract between the owner and a commissioning authority. The commissioning process is classified into four types: 1) initial commissioning, 2) re-commissioning, 3) retro-commissioning and 4) on-going commissioning (continuous commissioning) according to whether the building system targeted are new or not, whether commissioning is continuously implemented or not, etc.

Figure 1 [1] shows definition of phases with stages and steps, typical topics at phase interface, important procedures in each step and definition of various commissioning process.

### **1.2 How commissioning differs from similar processes?**

TAB (testing, adjusting and balancing) vs. FPT (functional performance test): It is not always easy to define differences between the two. Functional performance testing is the focus of acceptance commissioning, which is the process of determining if the system is completed to satisfy owner's project requirements, to meet with final design intent and to show the performance requested. It should be extended another year after completion in order to clarify seasonal and/or yearly performance. It verifies that the equipment, subsystem and total system work with their harmonization (including the stability and durability) to show the final function of building air-conditioning, and the objective environment written in design documents can be realized within energy consumption predicted. The dynamic performance, partial load performance and seasonal performance for HVAC equipments are very important in this sense.

Thus, the functional performance testing of equipment lays emphasis on the harmonization in the system, and is differentiated with testing, adjusting and balancing on the performance of equipment itself.

ESCO vs. retro-commissioning (RCx): Retro-Commissioning means the first time commissioning being implemented in existing building in which a documented commissioning was never implemented before. In many cases, design documents of the existing building have been lost or unmatched with the current situation. Therefore, the retro-commissioning process would include verification matters on the design as shown in parts of initial commissioning. Basic difference from ESCO originates in the form of payment for expenses. As described before, RCx expense is paid as professional fee irrelevant to actual pay back expected, while, as well known, ESCO pursues maximum profit and pays expenses by actual, but estimated on a baseline energy model, fruits due to energy saving. Also, the environmental quality is put aside in case of ESCO, if not worsen it, while RCx targets improvement of environmental quality as well, which certainly effects the difference of results.

Most people may think that ESCO is better than RCx, because the owner will never lose money as ESCO pay money for retrofitting and owner looks just enjoy energy cost reduction, however RCx should request owner to pay money regardless of degree of energy cost reduction. It should not be forgotten that there is a pitfall here that ESCO necessarily targets realizing maximum performance/cost items in a short range, that critical items which may largely effect the environmental performance as well as energy performance and only could be judged in a long range, and that there will be more errors in estimating energy cost reduction due to lack of data and precise but complicated tools which are not available in a limited time and cost for bidding. This often results in familiar items such as changing lamps, adding pump inverters and exchanging low-efficient machines with high efficient ones. However, diagnosing technology becomes substantially similar, if the cost for diagnosing could be neglected. .

Diagnosis for energy saving vs. RCx: Diagnosing procedure for energy saving may exist just between ESCO and RCx, because actual diagnosis for energy saving for a certain building and systems are either one day free diagnosis service by Energy Conservation Center of Japan or detailed but currently free diagnosis by potential contractors of the retrofit works following later. Putting the former style aside due to its preliminary character, the latter procedure will be taken when the system is clearly degraded and needs renewal and ask potential contractors to diagnose the system performance with a bargain that the company will be asked to do retrofit works later. In this case tools applied depend on the scale of retrofit and quality of diagnose sometimes may be more detailed than RCx business based on commissioning fee, especially when the .research fund is to be invested from the owner.

## **2. HOW COMMISSIONING DEVELOPED?**

### **2.1 Brief history in Japan and world**

Figure 2 compares brief history of development of commissioning process system in Japan comparing with other world. It is said that discussions on HVAC commissioning had come on the table during 1970s in UK and USA but actual activities to establish commissioning guidelines began after mid 1980s. In UK, the guideline having been prepared by CIBSE/BSRIA (CIBSE: Chartered Institute of Building Services Engineers, BSRIA: The Building Services Research and Information Association) are rather close to TAB technical guidelines but the first issue was "Division of Responsibilities" [2] in 1988. ASHRAE issued the first guideline in 1989 as "The HVAC Commissioning Process" [3]. In Asia, Hong Kong experienced commissioning concept in early stage of 1980s due under the British reign.

Japan enjoyed the bubbled economy during 1980s but suffered degradation of building quality as well as HVAC quality due to the lack of engineers. The author alarmed on it and introduced discussions on building commissioning in USA, ASHRAE symposium in 1986, at a certain meeting. Just after this timing, I had the chance of participating in the

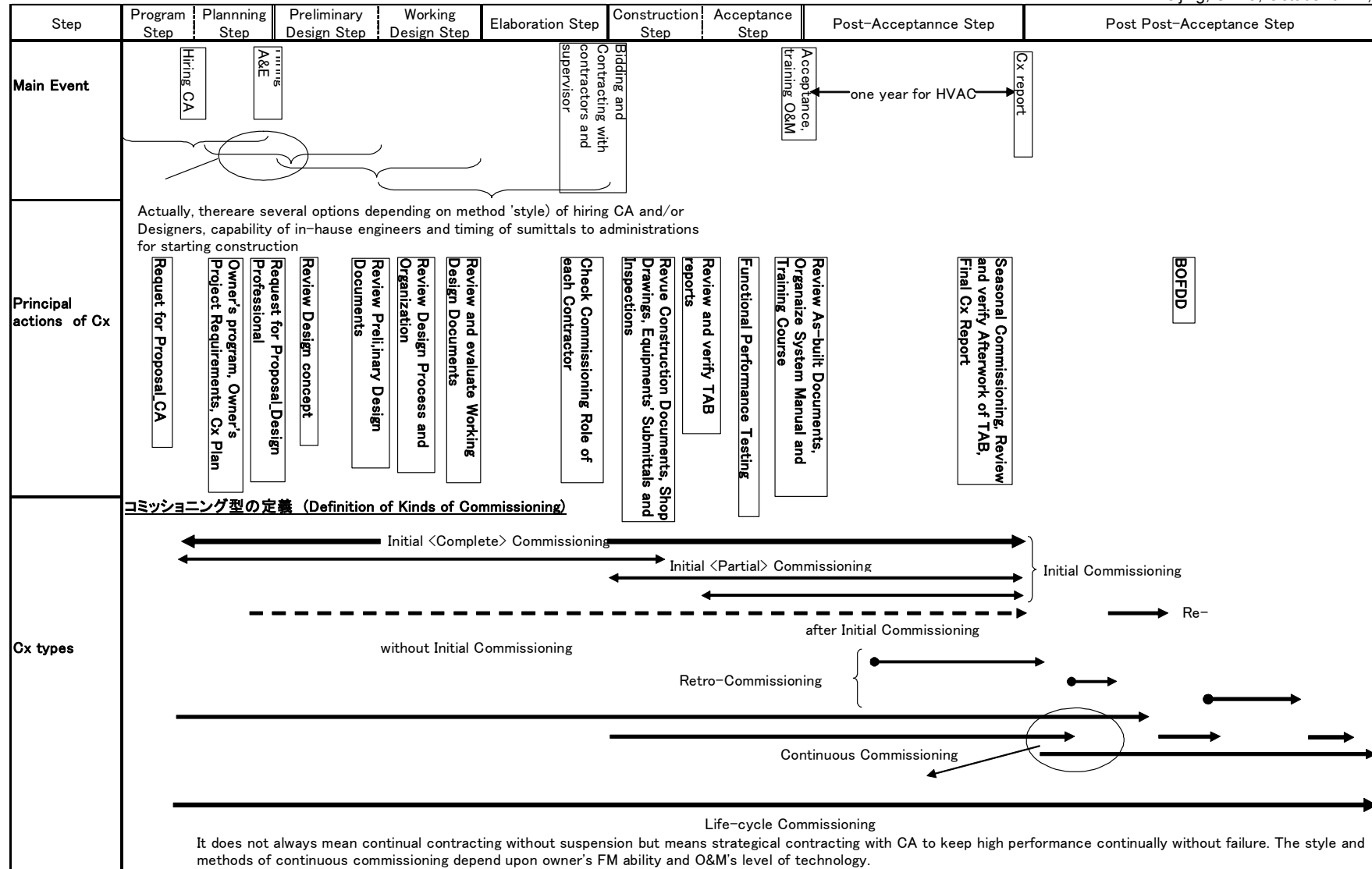


Figure 1. Phase and step definition, typical topics at phase interface, important procedures in each step and various commissioning definitions

study for IEA/ECBCS/Annex 16 and 17 for establishing BEMS user's Guideline and Evaluation/Emulation technology, which later continued to Annex 25 and 34 for BOFD, the building optimization, fault detection and diagnosis, and Annex 40 for HVAC commissioning process, just as lifecycle study of the author. During these years he could preside over Japan domestic activities related to these kinds of international moves on Commissioning and BEMS, among which ISO BACS-related standardizing activity now going on, too.

<u>World</u>	<u>Japan</u>
<ul style="list-style-type: none"> <li>• 197? Cx activities began in USA</li> <li>• 197? Cx activities began in UK</li> <li>• 1979 ASHRAE symposium on TAB</li> <li>• 1986 ASHRAE symposium on Cx</li> </ul>	
<ul style="list-style-type: none"> <li>• 1988 First CIBSE code on Cx issued in UK</li> <li>• 198? Cx activities began in HK</li> <li>• 1989 First ASHRAE Cx Guideline issued</li> <li>• 1991 Annex 25, BOFD and real time simulation, started</li> <li>• 1993 First NCBC, National Conference on Building Cx</li> <li>• 1995 Annex 34, BOFD Demonstration, started</li> <li>• 1996 Second ASHRAE Guideline on Cx Process issued</li> </ul>	<ul style="list-style-type: none"> <li>• 1987 First introduction of Cx concept by NN</li> </ul>
<ul style="list-style-type: none"> <li>• 1999 Building Cx Association (US) established</li> <li>• 2000 Annex 40, HVAC Commissioning Process</li> </ul>	<ul style="list-style-type: none"> <li>• 1991 Participated in Annex 25</li> <li>• 1995 Participated in Annex 34</li> </ul>
<ul style="list-style-type: none"> <li>• 2002 ASHRAE/NIBS Cx Process 200X-0(Public review draft)</li> <li>• 2002 Cx Center established in HK</li> </ul>	<ul style="list-style-type: none"> <li>• 1997 Cx activitis began, BEMS Committee, SHASEJ</li> <li>• 1998 Tentative Cx Guideline Draft developed</li> <li>• 1999 Cx Committee established in SHASEJ</li> <li>• 2000 Participated in Annex 40</li> <li>• 2000 First formal application of Initial Cx, results publicized in 2001</li> <li>• 2002.9 Organaized Sessions on Cx, SHASE Academic Meeting</li> </ul>
<ul style="list-style-type: none"> <li>• 2004~2005 First ACBC, Asian Conference on Building Cx?</li> </ul>	<ul style="list-style-type: none"> <li>• 2003.3 Draft Cx Guideline issued and Cx symposium held</li> <li>• 2003.4 Annex40 Kyoto mtg. with international symposium on Cx held</li> <li>• 2004 First Cx Process Guideline to be issued</li> <li>• 2004~2005 First ACBC, Asian Conference on Building Cx?</li> </ul>

Figure 2. Development of commissioning process, world and Japan

## 2.2 Experience of BOFD study

The term BOFDD, or BOFD, the building optimization, fault detection and diagnosis in operation and control has come to be recognized among HVAC experts owing to the IEA Annex activities. (Hyvarinen et al., 1996) Nakahara defined the BOFD as follows [4] [5] and established total BOFDD, or life cycle commissioning, system as shown in Fig.3. The system is hierarchically composed in the maintenance stage of the figure. The higher stage BOFDD is meaningful only after the fault recovery at the lower stage. Each stage consists of three steps, from right to left, the fault detection, fault diagnosis and fault recovery. Tools for BOFDD to be used in each stage are mostly common with those used at the design stage, which are the simulation, mathematical models, database and expert systems.

*Building optimization is the process of minimizing an overall objective function that includes all cost of building operation (e.g., energy, maintenance, personnel) with the constraint of environmental condition. The building optimization can be performed with respect to both design and control variables. When the substantial object of building optimization is reflected, the measures will even include manual operation using BEMS, the retrofit of building services systems and thermal and optical performance of the building structure from the viewpoint of building management.*

A design necessarily includes faults and unknown factors at the design stage, so that it should be inspected and modified in order to meet the client's newest need at the time of completion and the maintenance stage during operation which will be defined by the facility management. Recent computerization of design process greatly contributed to mass production of drawings and keeping beautiful appearance but the average quality of design has rather been lowered, because the expert system is not yet fully developed and the real expertise is losing its situation to introduce it into actual design. Thus, contrary to a frequent talk of the optimization, the way to the optimal design and operation is difficult to find out its way.

Figure 3, BOFDD structure [1][4], also shows the process of the life cycle building optimization in which the production stage as well as the operation stage is closely related through simulation techniques, fault detection and diagnosis by mathematical model, existing data base, statistical analysis, control strategy and commissioning. The design without narration of control strategy is ultimately defective. The control strategy at the design phase, which should be simulated beforehand to assure the effect, must have the same kind of performance function and constraints which will be followed at the operation stage. Commissioning has thus become an important keyword of optimization for realizing optimal building environmental system with the indoor air quality as the constraint and the energy consumption as the performance function from the life cycle point of view. This kind of commissioning system is not yet fully functioning in any country. However, who on earth can fairly advise the client through the life of the building? The architect has

never reflected the maintenance stage, neither does the HVAC designer, for only designing is their profession.

Thus, the ideal commissioning process should begin just after the schematic project plan is established by the owner. The commissioning authority is responsible for finding out any faults within design, the process and content, and acting as an intermediary among the designer, constructor and the client in case of any change is needed. He should also be responsible for making sure that the system as well as the building can be operated as the predicted performance from the energy, environment and facility management point of view for at least two years. This will make the life cycle optimization possible as shown in the figure.

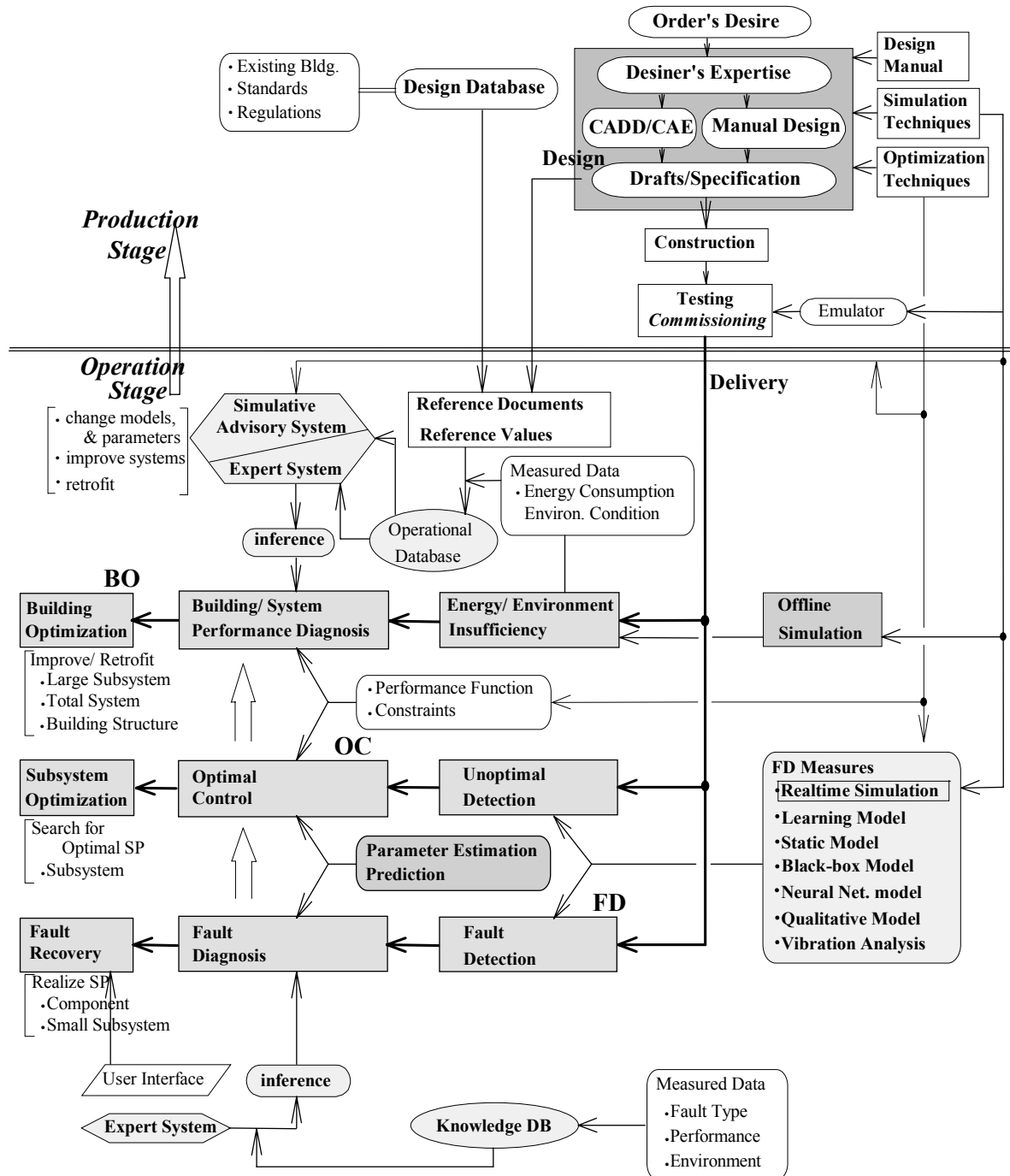


Figure 3. Total structure of BOFDD and life-cycle commissioning

### 3. HOW WAS THE FIRST CASE OF INITIAL COMMISSIONING PROCESS IN JAPAN MANAGED?

The author and WG started establishing SHASEJ commissioning guideline in 1996. After establishing its first draft and during revising works the author proposed a building owner who was just at the start of constructing its new

office and laboratory facility to apply commissioning process as a first model application in Japan. Yamatake Corporation agreed to offer him the situation to act as CA, the commissioning authority, for their new research center for Yamatake Building Systems Co. Ltd., to be called as YBS hereafter, in the spring of 2000, just at the stage of starting construction. Happily, both the design office and construction company are of the top-class in Japan in their high quality business. They were pleased to cooperate on the commissioning project, in the condition that applying commissioning process would not disturb the critically short-term project. Not being the complete initial commissioning process that would start at programming phase, it was needed to quickly pass the construction preparation procedures, i.e., post-facto program commissioning and post-facto design commissioning, before entering construction phase commissioning.

### 3.1 Project Outlines

Outlines of building and HVAC system [6]: The outline of the project is as follows. The scale of the building and HVAC system is rather small but included lots of challenges for energy conservation and optimal air-conditioning for human occupancy and for environmental research. The period of construction allowed was very critical.

- Building Name: Yamatake Environmental Engineering Research Center
- Location: South west of Tokyo (where we have four seasons clearly recognizable)
- Use: Office space and laboratory that has a thermal chamber to simulate an office room and surroundings in terms of thermal environment.
- Scale: 1,700 m<sup>2</sup> (will be expanded as the Central R&D Center of Yamatake Group)
- Structure: Steel construction, four stories above the ground
- Heat Pump Chiller: 56kW(15TR) for cooling, 63kW for heating, with 60m<sup>3</sup> of water thermal storage tank
- Brine Chiller: 50kW(14TR), with 8m<sup>3</sup> × 370kWh of ice thermal storage tank
- Brine Chiller: 250kW(60TR)
- Conceptual Design: May – Sep 1999
- Detail Design: Oct 1999 – Feb 2000
- Construction: Feb – Sep 2000

Design concept for indoor environment and energy conservation [7]: Principal design concept for energy conservation and new technologies are as follows. Combination of passive design and active design was applied to each floor in different manners. Figure 4 shows building appearance, piping diagram around heat source system and HVAC system of office block.

#### (1) Passive measures

- 1) Natural ventilation in intermediate season with stack effect
- 2) Night purge
- 3) Utilization of ground thermal storage effect for outdoor air intake
- 4) Double skin window to make use of solar gain in winter and solar protection in summer
- 5) Light shelf to introduce daylight
- 6) Daylight control

#### (2) Active measures

- 1) Lighting control by time scheduling, passive sensors and an access control system
- 2) Task & ambient system using under-floor air supply and other method for experiments
- 3) VAV and VWV
- 4) Use of *Coanda* effect to wall horizontal wall supply
- 5) Slab thermal storage and radiant heating & cooling
- 6) Water and ice storage

Engineer's estimation for primary energy consumption at the office spaces was 1GJ/a/m<sup>2</sup> that is about 30-40% less than that of typical office of this scale, that is, 1.4GJ-1.7GJ/a/m<sup>2</sup>. Rough diagram of piping for office spaces and laboratory thermal chamber are shown in Fig.4. Motivation of commissioning: The owner's motivation to perform commissioning as a first trial on commercial buildings in Japan is as follows: [6]

- 1) The owner will have his building, which is well operational at the beginning of its use and function as intended.
- 2) Members concerned will understand the real commissioning process and problems which will contribute to the research of a learned society such as SHASE, propagate good commissioning practices and may create new business opportunities.

### 3.2 Commissioning Procedure

Organization [6]: Figure5 shows organization to implement the YBS commissioning project. Commissioning management team consists of CA, ACA and ACM as shown in the figure. The ACM, or Assistant Commissioning Managers, is basically non-paid volunteer group from the design professional, general contractor and control contractor who belongs

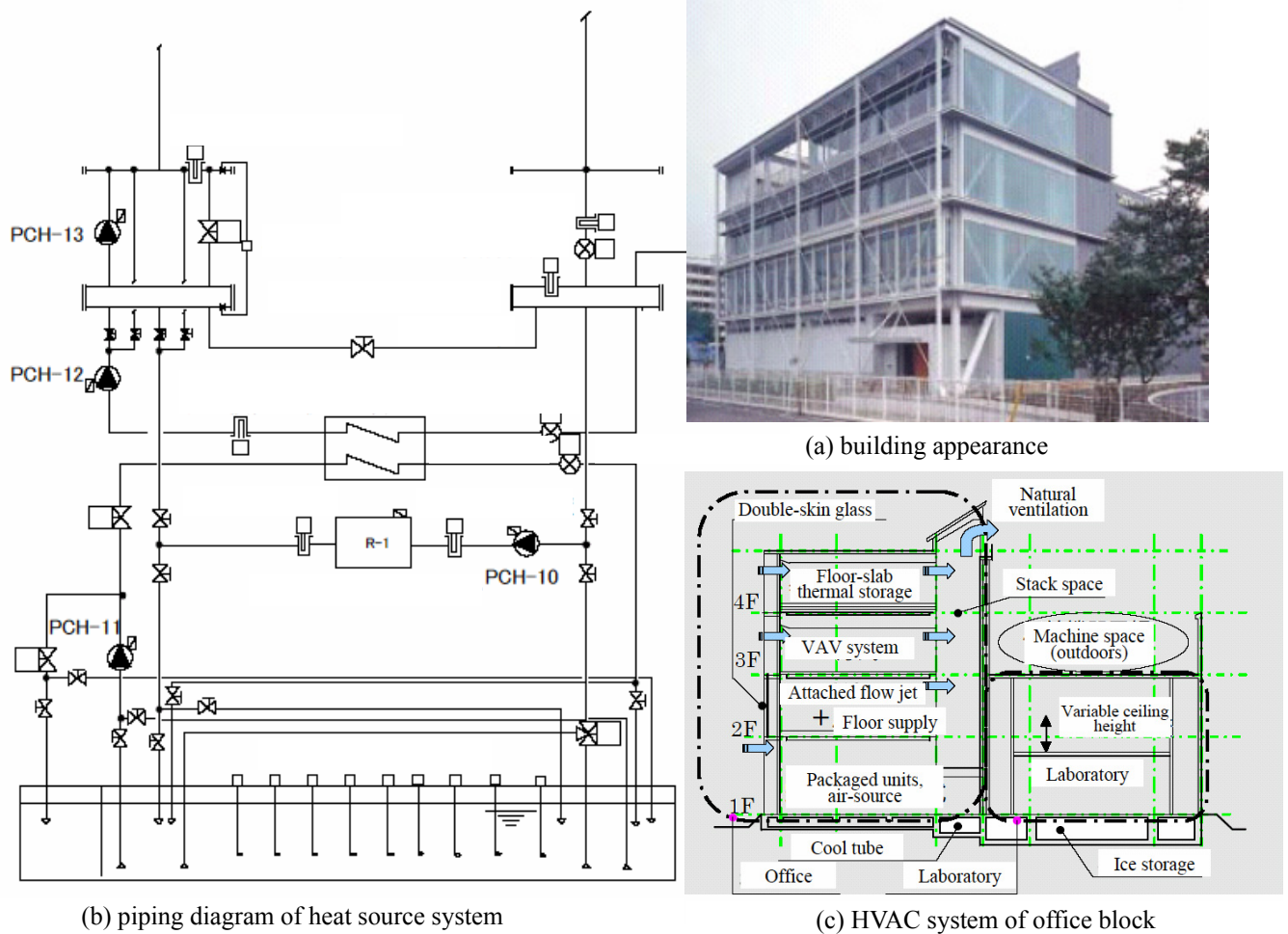


Figure 4 Outline of YBS building and HVAC system

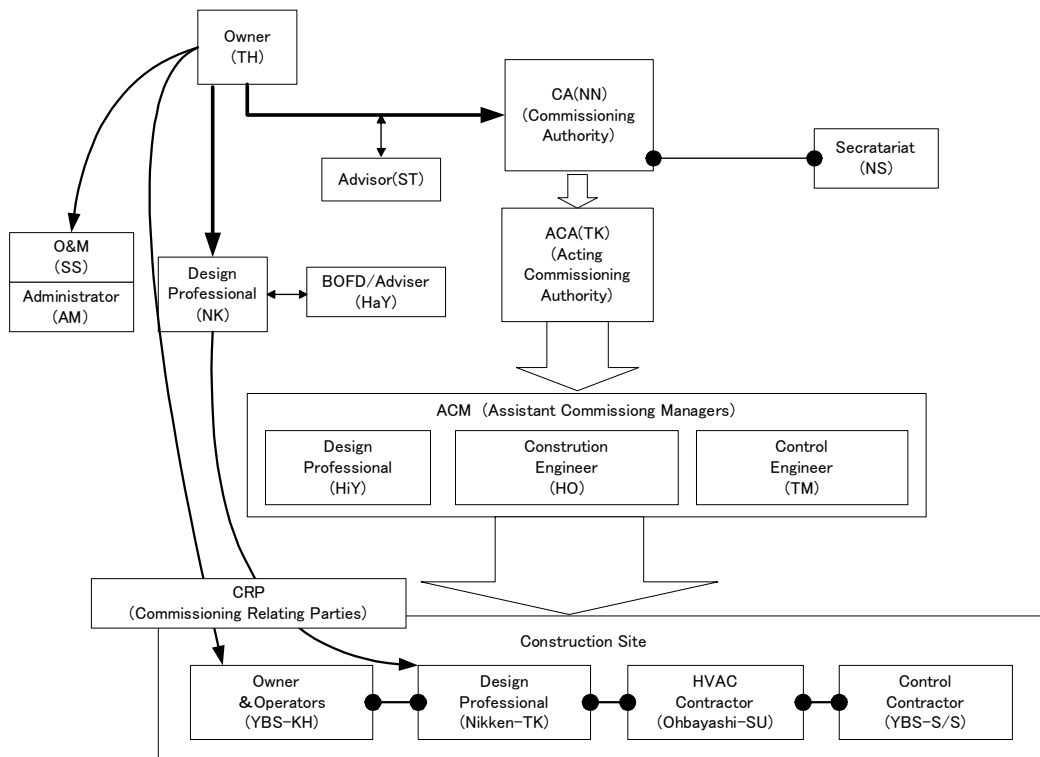


Figure 5. Organization of YBS commissioning project

to the owner at the same time. As mentioned before, this is a model project to study and establish an effective commissioning procedure in Japanese culture and related with academic activity of SHASE commissioning committee, each party included in ACM was in favor of this process without any additional overheads. Therefore, in case of business-based project, ACM is not the volunteer and should be hired on necessary. Actually, each member of ACM as well as CA and ACA did big jobs for making typical formats that could be used in any commissioning project. The BOFD/ adviser was included in order to plan, develop and verify BOFD tools that may be combined with the research in Annex 25, Annex 34 and a New Annex, to be established later as Annex 40.

All members, who are the commissioning management team plus CRP, the commissioning relating parties, forms a commissioning promoting conference. Contractors include TAB jobs in their contracting scope according to the custom in Japan. The final part of commissioning procedures was frequently devoted to how to discriminate TAB and commissioning at the acceptance phase.

Commissioning process [8][9]: Figure 6 shows outlined commissioning schedule and process. As shown in this figure, this building project had so tight a construction schedule that TAB works by contractors as well as commissioning works for acceptance could not finish before the start of occupancy. The author was hired as CA during the construction step, acceptance step and post acceptance step. Also he acts as the consultant engineer for the following post post-acceptance commissioning, or continuous commissioning of the facility, thereafter.

Methods of functional performance test for acceptance commissioning [10][11][12]: After verifying TAB results for each components and subsystems, functional performance test is to be performed. Basic idea for the test is to trace definition by ASHRAE Guideline, 1996, on commissioning, which says. *Commissioning is the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. Commissioning begins with planning and includes design, construction, start-up, acceptance, and can be applied throughout the life of the building.* Underlined parts with real lines are the scope of this acceptance commissioning. Because this process began after designing practice, the commissioning team is not responsible for the parts with dotted underlines but recognized he should predict performance and suggest best operation policy under the design intent document which was prepared as *post facto* document.

The methods of testing are itemized as follows. Detailed discussion on the methods is not the intent of the present paper.

(1) Order of test, in view of main HVAC systems: Office oriented HVAC systems shall be tested at first, and then laboratory experiment oriented HVAC systems will be tested.

(2) Order of test, in view of subsystems for office HVAC

- 1) Heat pump
- 2) Water thermal storage system
- 3) Pump and piping system
- 4) Air handling unit and duct system
- 5) BEMS

(3) Order of test, in view of functionality

- 1) Verification of TAB results
- 2) Equipment on-off, in both manual and automatic mode,
- 3) Performance and operation status of pumps and fans, comparing with characteristic curves
- 4) Open-loop performance test on heat exchangers, AHU coils, water-to-water heat exchangers, air to air heat exchangers, to check system faults, equipments' rated capacity, piping/ducting faults
- 5) Closed-loop control test, by changing control set-point, to check PID parameter optimality
  - peak cooling condition mode
  - medium cooling condition mode
  - medium heating condition mode (later in heating season)
  - peak heating condition mode (later in heating season)
- 6) Detailed check on thermal storage and HVAC controls and limit check
- 7) Specific system performance check
  - Natural ventilation during intermediate season
  - Slab thermal storage system for conference room
- 8) Trace the system operation manual and set at normal operation mode

Data shall be adopted through BEMS and to be analyzed off line but immediately. Results shall be documented and faults found, if any, shall be corrected immediately, as soon as possible. A paper [14] on the open-loop and closed-loop tests was referred in planning these procedures.

### 3.3 Findings of the commissioning process [13]

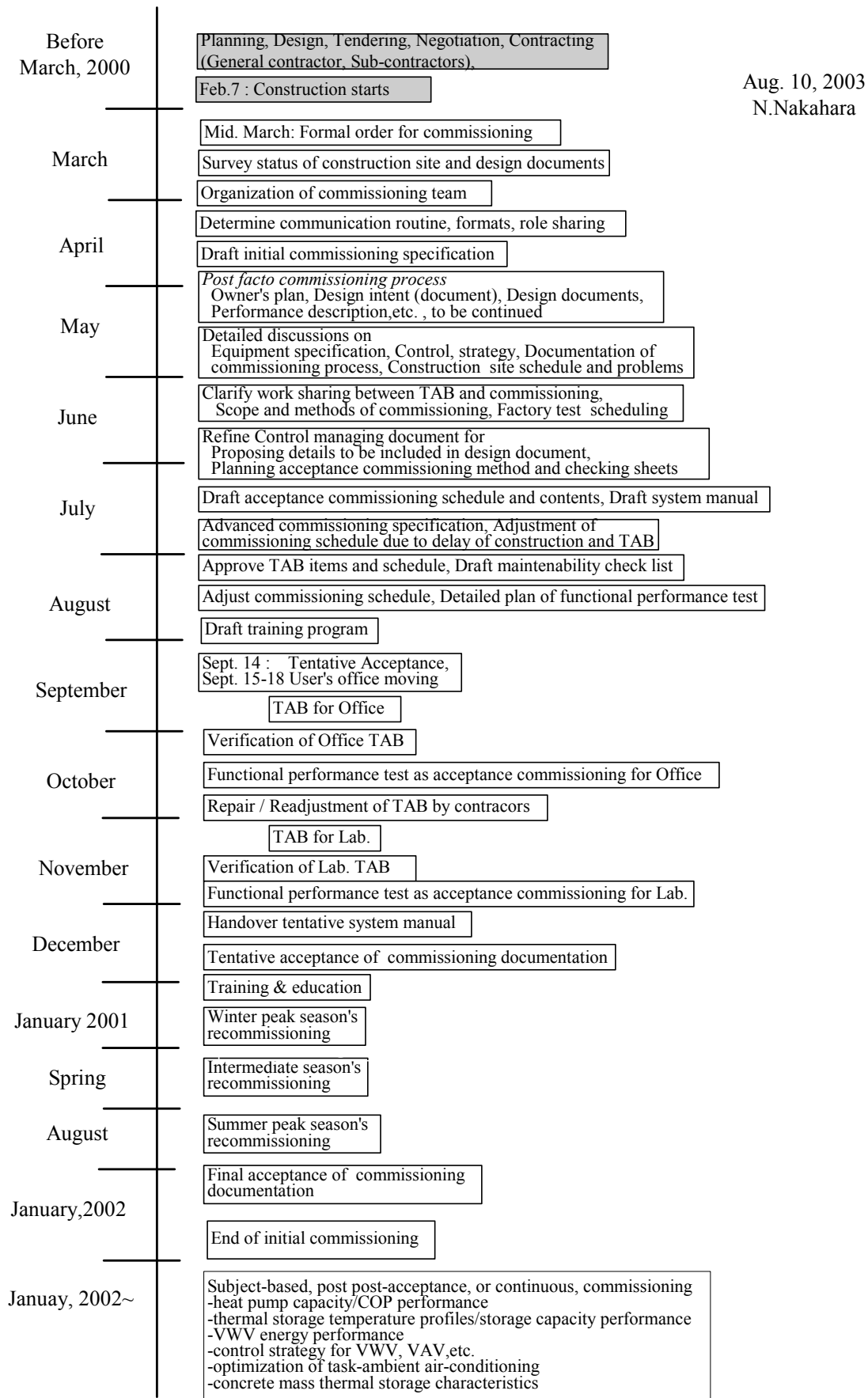


Figure 6. Commissioning process outline

- 1) Tracing back to the program phase and design phase, the documents such as Owner's Program and Design Intent were created referencing minutes of the meetings between the owner and designers, conceptual design and detailed design documents. In Japan, to establish formal Owner's Program and Design Intent are not always common practice currently.
- 2) Reviewing and commissioning the design and the construction process, more than 100 clarifications and recommendations have been pointed out as the *post facto* commissioning.
- 3) Examples of Clarifications and Recommendations for the design and the construction by CMT.
  - Need to document actual controlled performance for environmental condition to guarantee in design document, not only the calculation criteria.
  - Need to know the reason of vender selection in terms of durability, maintenance system, guarantee terms, popularity and actually measured performance data in addition to unit prices.
  - Need to have a pit for pumping up water of the water thermal storage.
  - Need to consider eliminating pump (PCH-12) to simplify control, prevent miss-operation, conserve energy.
  - Need the design clarification of thermal equation regarding task-ambient air conditioning system
  - Need to move the humidity sensor to intake side of the return fan.

#### 4. HOW ARE COMMISSIONING TOOLS CLASSIFIED?

Commissioning tools are divided into Non-technical tools and technical tools. Both are indispensable for successful commissioning implementation.

##### 4.1 Non-technical tools

Non technical tools are consisted of guidelines, manuals, process control tools and documentation tools, that is, templates of documents, forms and formats. Guidelines define standard commissioning process and terminology, role sharing and obligations of each commissioning relating party, especially of commissioning authority, the CA, and some annexes for further understanding of the process and its implementation. The ASHRAE Guidelines for commissioning process, both 1996 [15] version and 2002 draft version [16], are the most famous examples of it.

Manuals provide either detailed technical guides or templates for documentation at executing actual projects as CA who is hired by the owner as a principle and responsible for whole the commissioning process from program step to post-acceptance step in case of initial commissioning process. A series of BSRIA/CIBSE commissioning manual is good examples of the former. The functional test guides which are recently keenly under preparation in several organizations such as PG&E (Pacific Gas and Energy), PECI (Portland Energy Conservation, Inc.) and LBNL (Lawrence Berkeley National Laboratory) in joint [17] and ESL /TAMU (Energy System Laboratory, Texas A&M University) are detailed semi-technical guide for the functional performance test that is one of the focus of the initial commissioning process. The DOE-sponsored PECI Model Commissioning and Guide Specification [18] is one of the complete example of the latter, which were prepared primarily for GSA (General Administration Services, USA) but which can be conveniently used for private commissioning businesses. Forms and formats are provided in compliance with guides and manuals as templates. Any guides, manuals, forms and formats will include actual filled-in examples and model documentations.

An example of process control tool is MQC matrix for commissioning developed in Japan for IEA/Annex 40 study (Commissioning of Building HVAC Systems for improved Energy Performance) of which idea originated in The Netherlands linked with building regulation on indoor air quality [19]. Modified MQC is to define commissioning process typically for initial commissioning process and lists up each action and related activities, requirements, tools and documentation for each phases and steps of commissioning. Under each cell item there are more detailed descriptions of the cell contents in which detailed specifications, URL to be referred, e-mail addresses of related parties under the present commissioning process and other files to be linked. The MQC will be prepared for standard model for various types of buildings and for the dedicated MQC to specific projects. The former one, to be called as SMCP/MQC, can be used for the latter remodeling by adding, deleting standard contents, inputting new contents and links. Figure 7 shows the structure of SMCP/MQC [20]. A SMCP/Annex40 is also under development by French CSTB team for Annex 40 study that could be looked at on the Annex 40 website [21] after completion. (Note: SMCP means Standard Model Commissioning Plan)

##### 4.2 Technical tools [22]

Automatic commissioning tools: Technical tools herein defined include mathematical tools and measure/analysis tools. Objectives of commissioning tools are, a) checking of the performance at the design phase, b) performance test, c) functional test, d) FDD of HVAC components and systems, e) FDD of logical/ system/ components of BEMS, f) detecting faulty design or specification, g) detecting faulty installation of components, h) checking completeness of TAB work and, i) training of building owner and maintenance personnel.

Commissioning tools may be either manual or automatic. The merits of automatic commissioning tools are a) re

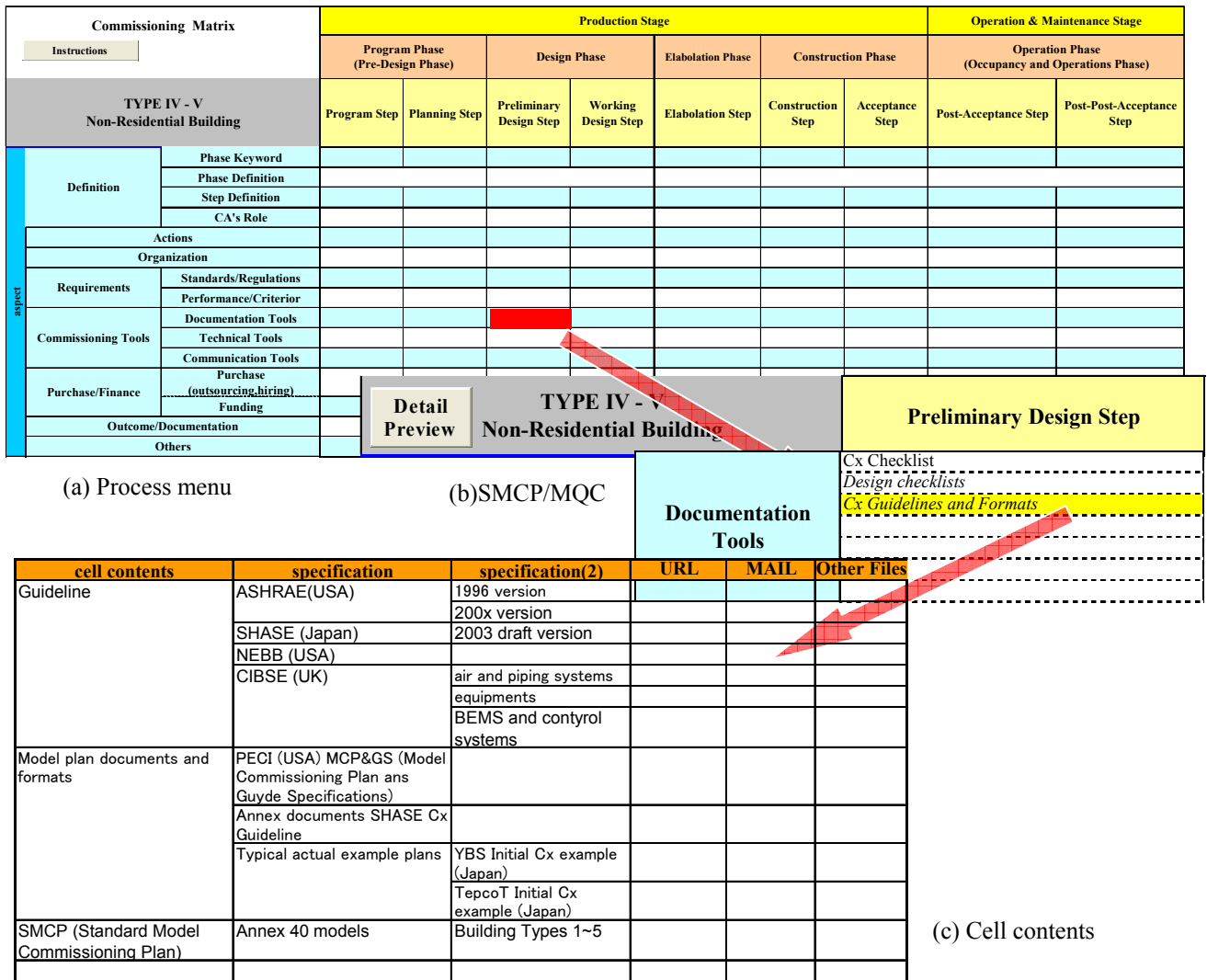


Fig. 7 MQC matrix, Commissioning process control tool

ducing time for commissioning, b) reducing cost for commissioning, c) preventing mistakes in commissioning, d) reducing the required number of commissioning experts and e) performing commissioning under the condition out of design condition by using modeling technology.

**System simulation:** HVAC System simulation programs have been used for comparative study of energy effectiveness of various HVAC systems. Some programs aims at analyzing control behavior and/or room environment. Most of their target phases are design phases for the sake of HVAC designers. Actually, however, lack of time for design, lack of skill for program handling, lack of credibility for total system simulation results and many other reasons caused rare application to actual HVAC design except in the case that any law regulates to use them for, e.g., energy conservation and green building design. However, several reasons may urge HVAC designers and engineers to use simulation programs in the future as follows.

- User interface to input data and select proper items among options has become very friendly and simple through interactive operations with the use of *Windows*.
- Energy efficient and/or green building design has become more and more socially requested aiming at fulfilling Kyoto protocol on global environmental issue.
- Needs for fault detection/diagnosis and commissioning and for verifying system performance for performance contract request more precise, verified and multi-functional simulation programs such as HVACSIM<sup>+</sup> and EnergyPlus.

Then, simulation programs as the commissioning tools are classified as Table 1. Table 2 shows in which phases or steps of commissioning process these simulation programs are used. Thus, HVAC system simulation programs will become indispensable tools for design and commissioning of HVAC systems. Hence it is necessary to make sure of the accuracy of simulation results compared with actual operation results.

Table 1 Simulation programs as commissioning tools

classification		examples
Heating/cooling load calculations	Peak load	Micro/Peak (Japan)
	Annual load	Hasp/ACLD (Japan)
Total HVAC system simulations Energy performance simulations	Static simulations	Hasp/ACSS, BECS/CEC (Japan) DOE2, BLAST, EnergyPlus (USA), ESP-r (UK) Dest (Tsinghua, China)
	Dynamic simulations	HVACSIM <sup>+</sup> , [TRNSYS], [EnergyPlus]
Simulations for specific sub-systems		Thermal storage system: TESEP-W (Japan) Solar system: TRNSYS
Room air distribution and environmental distribution	Macro-model	Block-model, R-model (combined complete mix. and piston flow model) (Japan)
	Micro-model	CFD programs, such as <i>STREAM</i>
Control system simulations		MATLAB, LABVIEW, HVACSIM <sup>+</sup>

Table 2 Use of simulation programs for commissioning process

Cx. process	programs and design phases for initial commissioning							Re-commissioning, Continuous commissioning
								Retro-commissioning
phase	Program		Design		Construction		Operation and occupancy	
step	Program	Planning	Preliminary design	Working design	Construction	Acceptance	Post-acceptance	Ordinary operation and occupancy
Cx. of energy performance	<ul style="list-style-type: none"> <li>* Estimation of annual energy consumption</li> <li>* Optimizing air-conditioning zoning</li> <li>* Optimizing design and control parameters</li> <li>* Optimizing equipments' capacity</li> </ul>					<ul style="list-style-type: none"> <li>* Evaluation of energy performance</li> <li>* Continuous energy analysis</li> <li>* Quantification of energy saving effect</li> <li>* Identify baseline energy model</li> </ul>		
Cx. of environmental conditions	<ul style="list-style-type: none"> <li>* Dynamic characteristics of room environment</li> <li>* Seasonal evaluation of system performance</li> <li>* Analysis of control system dynamics</li> </ul>					<ul style="list-style-type: none"> <li>* Fault analysis on equipments and environments</li> <li>* Quantification of retrofit effects</li> <li>* Evaluating system dynamics</li> <li>* Stability evaluation and optimal tuning</li> <li>* Real time simulations for BOFDD</li> </ul>		

## 5. COMPARATIVE STUDY OF SYSTEM SIMULATION PROGRAMS AS COMMISSIONING TOOLS

In order to examine and compare availability of HVAC system simulation programs which are popular, or at least popularly known in the world, or in the author's cooperative study group, a comparative study was made and reported in references [23]-[29] and summarized in this chapter.

### 5.1 Selected programs and comparison of typical functions [23]

Five programs were selected for comparison. The HASP/ACSS [24] was developed by SHASEJ in 1985 that has not actually been revised since then and cannot be said very often used and yet very famous in Japan. No graphical user interface has ever been sold out in the market except for a private version. EnergyPlus [25] the first version of which was issued in 2001 from LBNL, sponsored by DOE (Department of Energy), which is an extended version of both DOE2 and IBLAST and equipped with far more flexible functions than these and with capability of dynamic simulation as well as interfacing to foreign programs such as CFD and AUTOCAD in the future. DOE2 [26] was developed by LBL under the sponsorship of DOE in early 1980s, and has been often revised and most popularly used in USA, especially in case of regulated by laws or guidelines on energy conservation and/or sustainable building design. Graphical user interfaces has been progressively developed, such as *Power DOE*. Dest [27] was developed in Tsinghua University, China, since early 1990s and the first version was issued in 2000, which basically aimed at simulation-based building environment and HVAC design. Functions on energy and environmental evaluation are almost the same for these four programs, but each with peculiar algorithms due to their design concept. HVACSIM<sup>+</sup>(J) [28] is a Japanese version of original public domain program HVACSIM<sup>+</sup> that had been developed in NBS (presently, NIST) in 1985. It is a typical HVAC dynamic simulation program and it cannot be directly compared with other four programs. Table 3 shows comparison of typical simulation elements starting from weather data to HVAC system components and controls. In the last line actual building system that will be explained in the next section is compared with others.

## 5.2 Model building and HVAC system [23]

The model building and its HVAC system was composed of YBS building plan described before. The third floor having VAV system (see Fig.4 (c)) was adopted as model floor plan and model HVAC system and it was multiplied with ten to form 3,300 m<sup>2</sup> building with 30 kW of peak cooling load. The details of the system are described in references [7][10][12][23] and the floor plan only is shown in Fig. 8. Actual installation has two AHUs, each assigned to the east and west zones, each of which includes interior and perimeter zones. This assignment is not popular in the US application, so that AHU zoning was left free to the operator of each program. The calculation conditions, both common and differentiated due to difference of program characteristics and trivial lack of adjustment, are also described in the last column of Table 4. Hourly heating and cooling peak load was calculated by MicroPeak, a dedicated Japanese program for calculating peak load based on TAC/2.5% weather data.

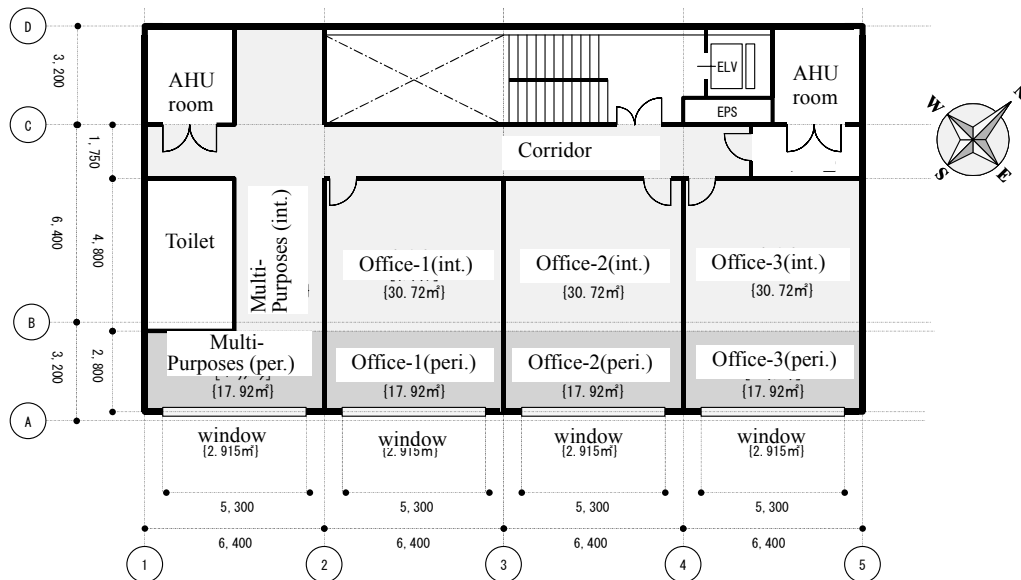


Figure 8. Model floor plan for comparative study of five simulation programs

## 5.3 Calculation results and discussions [29]

Calculated results are shown in Table 4, together with calculated peak load by MicroPeak at the top line and YBS actual data at the bottom line. Detailed discussions are shown in references [29] but important points to be discussed are listed below. Differences from common calculation conditions and program specific system application, which is listed in the last column, contributes difference of HER, or heat extraction rate from the coil, and energy consumption among simulation programs are listed in the last column of the table...

**Weather data:** Except for ACSS that uses SHASE format the weather data follows various kinds of formats in USA such as WYEC(Weather Yea for Energy Calculation,1983), WYEC2 (1997), NCDC(National Climate Data Center),TMY (Typical Meteorological Data, 1983), TRY (Test Reference Year, 1985) and TMY2 (National Renewable Energy Laboratory, 1995) and EnergyPlus uses text data in SI units. The HVACSIM<sup>+</sup>(J) uses SHASE format and converts it to its original format. Data for calculation was supplied from YBS measured one for 2002 and converted into each available format with several steps of treatment. Some data were missing and needs for supplementing and filtering method of irregular data obtained through actual measurements was thought indispensable.

**Peak load days:** The dates which show peak cooling and heating demand were not always the same but have similarities between programs depending on minor differences of load calculation algorithms for each program, as shortly shown in Table 3. Dates of daily peak load are listed in 'daily peak coil HER' column of Table 4 for each program.

**VAV system:** Japanese engineers often apply VAV system to heating mode, in which air distribution and IAQ tend to become worse, with heating coil in AHU, but no heating mode is equipped in US application, so that DOE2 and EnergyPlus are only applicable to VAV cooling with terminal re-heater at each VAV unit. Re-heating energy is always counted up as heating energy.

The VAV control algorithms and set-point value for supply air temperature reset as well as fan speed control are not the same among programs and left to operator of each program, which must have necessarily resulted not a little differences on HER and energy consumption. When original zoning is adopted and no air mixing is assumed between interior and perimeter zones at load calculation, both temperature rise and fall in peak seasons become abnormal with designed equipment capacities, so that in these programs that have no function of air mixing between zones the interior and perimeter was not divided as independent.

Table 3. Comparison of simulation functions among five typical programs

Program name	static / dynamic	weather data cakender	heat transfer calculation through opaque wall	energy mixing calculation between zones	selecting / structuring HVAC system	method of characteristics input of refrigeration machine / HP
ACSS	·static	·HASP format w/calendar ·holiday setting available	·response factor method (one hour calculation step)	·100% mixing during non-operation hours at night	·select from menu	·select from default characteristics or <u>input characteristic values by quadratic approximation</u>
EnergyPlus	·static + dynamic (future)	·MY2 format, basically, then converted to E/E(.epw) format w/calendar ·holiday setting available	·CTF method with solution by state space equations (variable time calculation)	·available but with fixed value (not to use presently as I/P are not separated)	· <u>select from menu (present) and/ or module type (future)</u>	·input regression coefficients
DOE2	·static	·FMT(.fmt) binary format and can be converted from various formats (TMY,TMY2,CTMY,WYEC,CTZ,TRY) w/o calendar ·US calendar and holiday setting available	·CTF(conduction transfer function) method (one hour calculation step)	·unavailable	·select from menu	·select from default characteristics or <u>input characteristic values by quadratic approximation</u>
DeST	·static	·TRY format	·direct solution by state space equations (one hour calculation step)	·available based on inputted ventilations per hour (both for operation hours and non-operation hours)	·select from menu	·select from default characteristics or <u>input characteristic values by quadratic approximation</u>
HVACSIM+(J)	·dynamic	·converted from HASP format w/calendar ·calendar can be input	·CTF method (ten min. calculation time step)	·available with a mixing model (both for operation and non-operation hour, and both for adjacent I/P and I/I zones)	·module method (arbitrarily structured)	· <u>define in the program source for specific equipments</u>
YBS actual system	—	—	—	—	—	—
Program name	characteristic input of fan / pump	VAV controls	outside air intake controls	heat transfer calculation of air to water cooling / heating coils	thermal storage system	notes
ACSS	· <u>select default characteristics</u> ·input characteristic values by quadratic approximation · <u>default for control characteristics</u>	·select a control type among two (min. air volume compensation or max. air volume compensation) ·OA intake volume is constant even at VAV	·min. OA intake cut ·OA cooling (economizer) ·total heat exchanger (heat wheel)	·dry part and wet part of the coil is separated in calculation, as well as equivalent simple wet coil model ·min water flow set at 10% by default. ·heat transfer coefficient is either <u>set constant with input air and water velocity</u> or recalculated at each timestep using air and water velocities	·water thermal storage system (multi-connected complete mixing tanks)	
EnergyPlus	·input regression coefficients (w/samples) · <u>default for control characteristics</u>	· <u>limited only to terminal reheat</u> · <u>fixed at min. air volume at reheat mode operation</u> ·air volume mode at VAV is selected among proportional to VAV, <u>fixed and scheduled</u>	·OA intake schedule control ·OA cooling (economizer) ·total heat exchanger (heat wheel)	·same as the model for HVACSIM+ but fixed as plate-fin coil	·none (except for Trombe wall)	·warm air supply is not applicable in case of VAV ·central type air-source heat pump is not included ·with or without VAV terminal reheating in cooling and all energy consumed at reheaters are summed up as the heating energy
DOE2	· <u>select default characteristics</u> ·control characteristics: input regressive coefficient for pumps, select default type for fans	· <u>limited only to terminal reheat</u> · <u>fixed at min. air volume at reheat mode operation</u> ·OA intake volume is constant even at VAV	·OA intake schedule control ·OA cooling (economizer) ·total heat exchanger (heat wheel)	·bypass factor method ·input bypass factor and rated cooling capacity and calculate air delivery state to suffice cooling capacity, inlet air state and air flow rate	·water thermal storage system (single complete mixing tank)	·intermediate season without air-conditioning is difficult to set up (can be estimated by deducting energy consumed in these months) ·central type air-source heat pump is not included ·VAV terminal reheat at cooling is always applied and all energy consumed at reheaters are summed up as the heating energy
DeST	· <u>select default characteristics</u> ·input regressive coefficient · <u>default for control characteristics</u>	·searchig control for min. energy point (space atate method) ·air volume mode at VAV is selected either fixed or variable	·min. OA intake cut ·occupancy demand control	·select equation to calculate either dry or wet raw of the coil judging from inlet air state ·for VAV air side surface heat transfer rate, fin efficiency, is recalculated · <u>equivalent simple wet coil model</u>	·water thermal storage tank (multi-connected incomplete mixing tanks)	·fixed amount of air infiltration is summed up in the outside air load ·weather data does not include cloud amount and wind velocity ·night radiation is not included
HVACSIM+(J)	·input regressive coefficients · <u>select types for control characteristics</u> (develop)	·controllable in arbitrary mode by design ·OA intake volume is variable at VAV	·defined by the user combining dampers and controllers	·border of dry and wet raw of the coil is determined as the result of heat transfer based on total heat calculation ·coefficients of heat transfer for both air and water sides are calculated in detail ·either plate-fin or round-fin can be selected ·heat capacity of the coil is taken into account because of dynamic calculation	·various types of thermal storage system due to definition (multi-connected complete mixing tanks/ temperature stratified tanks)	
YBS actual system	·(pump) pressure difference between headers set constant for bypass water	·load reset mode (Yamatate method)	·OA cooling (economizer) ·CO2 demand control	—	·multi-connected complete mixing water thermal storage tanks	—

Table 4. Comparison of simulation results among five typical programs

program names		yearly HER coil HER	daily peak coil HER	hourly peak coil HER	yearly power consumption (based on secondary and primary)				common conditions for simulations
					fan	pump	heat pump	total	
<b>MicroPeak</b> (Peak cooling and heating load)	cooling	— ( 15 (8/8)	4,098 kWh/d ( 15 (8/8)	447 kW ( 135 W/m <sup>2</sup> )					
	heating	— ( 6 (2/4)	1,734 kWh/d ( 6 (2/4)	196 kW ( 59 W/m <sup>2</sup> )					
<b>HASP/ACSS</b>	cooling	150 MWh/a ( 540 GJ/a) ( 164 MJ/a/m <sup>2</sup> )	3,022 kWh/d ( 11 (8/14)	378 kW ( 115 W/m <sup>2</sup> )	66 MWh/a	20 MWh/a	62 MWh/a	(secondaru energy total) 148 MWh/a	1. No separate zoning between interior and perimeter areas (I/P zoning) 2. VAV supply temperature reset: min. air compensation set at 40% 3. Fan VAV control: speed control with default characteristics OA intake volume is set constant in spite of VAV 4. Pump VWV control: speed control with default characteristics 5. Heating coil installed in AHU
	heating	32 MWh/a ( 115 GJ/a) ( 34.91 MJ/a/m <sup>2</sup> )	939 kWh/d ( 3 (2/4)	293 kW ( 89 W/m <sup>2</sup> )				(primary energy total) 1,518 GJ/a (per total floor area) 460 MJ/a/m <sup>2</sup>	
<b>EnergyPlus</b>	cooling	169 MWh/a ( 610 GJ/a) ( 185 MJ/a/m <sup>2</sup> )	3,298 kWh/d ( 12 (8/14)	525 kW ( 159 W/m <sup>2</sup> )	66 MWh/a	5 MWh/a	54 MWh/a	(secondaru energy total) 125 MWh/a	1. Air-conditioning area is divided into four with same area and no I/P zoning 2. VAV supply temperature is set at 18C and reset downward due to max. air compensation till 12C Lower limit of VAV air flow rate is 30% 3. Fan VAV control: speed control with default characteristics OA intake volume is set constant in spite of VAV In case of heating air flow rate set at the lowest 4. Pump VWV control: speed control with default characteristics 5. Heating coil installed in VAV terminal and operated only in winter 6. Heat source system: dedicated chiller for cooling, electric boiler for heating, characteristic of which was set the same as that of given AHP. 7. Room temperature SPs are 24C for summer and 20C for winter. Energy for reheat in summer and humidification in winter is not totalized. 8. Winter peak day is Jan. 21 among those normal weather data including correct solar data.
	heating	2 MWh/a ( 6 GJ/a) ( 1.82 MJ/a/m <sup>2</sup> )	154 kWh/d ( 1 (1/21)	57 kW ( 17 W/m <sup>2</sup> )				(primary energy total) 1,282 GJ/a (per total floor area) 388 MJ/a/m <sup>2</sup>	
<b>DOE2</b>	cooling	233 MWh/a ( 838 GJ/a) ( 254 MJ/a/m <sup>2</sup> )	2,871 kWh/d ( 10 (7/22)	420 kW ( 127 W/m <sup>2</sup> )	64 MWh/a	15 MWh/a	117 MWh/a	(secondaru energy total) 196 MWh/a	1. No separate zoning between interior and perimeter and no energy mixing between I and P is taken into account. 2. VAV supply air temperature set at 16C. 3. No VAV supply air temperature reset controls 4. Fan VAV control: speed control with default characteristics. OA intake volume is set constant in spite of VAV In case of heating air flow rate set at the lowest 5. Pump VWV control: speed control with input characteristics 6. Heating coil installed in VAV terminal and operated through the year and summed up in heating energy. 7. Heat source system: dedicated chiller for cooling, electric boiler for heating, characteristic of which was set the same as that of given AHP. 8. Energy consumption in April, May and October was deducted except for fan energy. 9. Winter peak day is Dec. 24 among those normal weather data including correct solar data.
	heating	29 MWh/a ( 106 GJ/a) ( 31.98 MJ/a/m <sup>2</sup> )	820 kWh/d ( 3 (12/24)	284 kW ( 86 W/m <sup>2</sup> )				(primary energy total) 2,012 GJ/a (per total floor area) 610 MJ/a/m <sup>2</sup>	
<b>DeSt</b>	cooling	157 MWh/a ( 565 GJ/a) ( 171 MJ/a/m <sup>2</sup> )	3,312 kWh/d ( 12 (7/22)	367 kW ( 111 W/m <sup>2</sup> )	55 MWh/a	16 MWh/a	70 MWh/a	(secondaru energy total) 141 MWh/a	1. No separate zoning between interior and perimeter and energy mixing between I and P is taken into account using input ventilation rate. AHUs are used dedicated for interior and perimeter zones. 2. VAV supply air temperature set above 16C in summer and between 14C and 32C in winter 3. VAV supply air temperature reset is searched for by predicted min. energy strategy. 4. Fan VAV control: speed control with input characteristics. OA intake volume is set constant in spite of VAV 5. Pump VWV control: speed control with input characteristics 6. Heating coil: installed heating coil in AHU 7. Weather data does not include cloud amount and wind velocity, which affects loads caused by infiltration and night radiation load. 8. Coil HER means the heating/cooling load at constant room temperature between 8 hrs and 18 hrs. 9. Winter peak day is Dec. 24 among those normal weather data including correct solar data.
	heating	19 MWh/a ( 68 GJ/a) ( 20.73 MJ/a/m <sup>2</sup> )	1,054 kWh/d ( 4 (12/24)	194 kW ( 59 W/m <sup>2</sup> )				(primary energy total) 1,446 GJ/a (per total floor area) 438 MJ/a/m <sup>2</sup>	
<b>Corrected actual results</b> (year 2002 measured for the 3rd floor, multiplied by ten)	cooling	180 MWh/a ( 648 GJ/a) ( 196 MJ/a/m <sup>2</sup> )	3,552 kWh/d ( 13 (8/8)	503 kW ( 152 W/m <sup>2</sup> )	77 MWh/a	13 MWh/a	117 MWh/a	(secondaru energy total) 207 MWh/a	1. Energy consumption in April, May and October was deducted from the yearly total data except for fan energy. 2. Energy consumption between 18 hrs and 8 hrs was deducted from daily total data. 3. Lower limit of VAV air flow rate is 30% OA introduction was adjusted as 360m3/h(720m3/h/floor) at the VAV min. air flow rate for each AHU. therefore, OA introduction increases at the higher VAV air flow rate. (The standard rate is 300 m3/hr for each AHU at the max. air flow rate) 4. Power for chiller and pumps are proportionally divided for the third floor based on HER and multiplied by ten to meet the simulation ncondition.
	heating	78 MWh/a ( 281 GJ/a) ( 85.09 MJ/a/m <sup>2</sup> )	1,708 kWh/d ( 6 (2/4)	319 kW ( 97 W/m <sup>2</sup> )				(primary energy total) 2,123 GJ/a (per total floor area) 643 MJ/a/m <sup>2</sup>	

HER: Heat Extraction Rate

AHU: Air Handling Unit OA: Outside Air

VAV: Variable Air Volume

VWV: Variable Water Volume

ASP: Air Source Heat Pump

I/P: Interior and Perimeter

Heat source and thermal storage system: Only Japanese programs, ACSS and HVACSIM<sup>+</sup>(J) can simulate typical thermal storage system used in Japan, that is, multi-connected complete mixing tanks and, in case of the latter program, temperature stratified tanks. Also, it is curious that air-source heat pump that generates heating energy in winter is not included in the heat source/sink menu.

HER at hourly peak load: Due to the difference of heating system and AHU supply air temperature set-point peak heating load have big deviations. Cooling HER is within 20% deviations on both sides with the average of MicroPeak calculation result.

HER at daily peak load: Cooling HER is within 12 % deviations on both sides with the average of EnergyPlus calculation result, with the same tendency of heating HER for EnergyPlus.

Annual HER: Except for DOE2 calculation result, all other programs have only six percent of deviations for cooling HER on both sides of the average value. The HER for both cooling and heating between actual result and DOE2 have almost same value but reasons are different. For DOE2's fixed supply air temperature control contributes a lot but actual result depends on much more outside air intake, because it was adjusted to introduce 360m<sup>3</sup>/h of outside air to each AHU at the minimum air flow rate of VAV, whereas simulation condition was set as 300m<sup>3</sup>/h at the design condition and set constant in spite of variable total air flow rate. Heating HER for Energy Plus has the same tendency as mentioned above. However, this trend of EnergyPlus calculation result for heating suggests that correct application of VAV system which restricts air supply only to interior cooling zone through a year and equips terminal or zone re-heaters to protect from excessive cooling, combined with a proper reset schedule of AHU supply air temperature, may realize optimal system with minimum energy consumption. This needs more research to draw conclusion from case studies.

Electric power consumption: Pump characteristic curve was not given and default characteristics were applied for each program, which may have resulted big difference between EnergyPlus and others. Chiller energy for actual results is far more than simulated values partly because annual HER has the same trend, and partly because actual temperature and humidity distribution was not the same as given, that is, 25C/55% for summer and 24C/45% for winter instead of 26C/50% for summer and 22C/50% for winter, actual heat pump COP was lower than the characteristic value, and each equipment may have had less energy efficiency in operating conditions which is most probable. Other reasons are to be identified by further study.

Annual primary energy consumption: Simulation results are within 10% deviations on both sides of Dest value and the order follows the magnitude of annual HER values. Actual consumption is the same as DOE2 value but it should be said only by chance and has no similar causes as mentioned before. Considering that design energy goal of original YBS building, from which typical floor plan and typical HVAC system were derived, was 1GJ/a/(m<sup>2</sup> of total floor area), 0.4~0.6 GJ/a/(m<sup>2</sup> of total floor area) of calculation results and actual result is no unreasonable value, because building energy consumption based on primary energy for HVAC is almost 50% of building total energy consumption.

## 6. CONCLUSION

HVAC commissioning process is most important process needed for design, construction and operation and maintenance of HVAC system to realize owner's true project intent and establish energy saving and sustainable operation and management of the building system. It was first applied in the building services engineering system in 1970s and during 1980s to 1990s commissioning manuals and guidelines was issued in UK and USA. At first it was rather discussed as a kind of extended TAB, testing adjusting and balancing, but now it is considered as realizing process of owner's program requirements, OPR, through program phase to design phase, construction phase and acceptance and post-acceptance steps, with strong stress on energy conservation, sustainable building design as well as optimal indoor air quality.

The present paper has introduced how commissioning is defined, how commissioning differs from similar processes, how commissioning is classified and developed and how commissioning tools has been developed in relation to BEMS and BOFD, building optimization, fault detection and diagnosis, international studies. The author has then introduced how he led establishing Japanese commissioning guideline since 1997 and, in order to accumulate practical experience necessary to get accustomed to commissioning concept and procedures, explains his experience of the first application of initial commissioning process as CA in Japan.

After discussing how and what commissioning tools shall be and introducing what an SMCP, standard model commissioning process, expressed by MQC matrix is like, the author explains about a comparative study of HVAC system simulation for evaluating energy performance supposing that it must be useful at design commissioning and post acceptance commissioning and/or continuous commissioning, especially in case for performance contract. Five programs, actually four for annual energy study purpose, HASP/ACSS, EnergyPlus, DOE2 and Dest were selected for comparison. The objective plan and systems were modeled from the building for which the author worked as CA, commissioning authority, in order to make possible to compare with actual result to evaluate applicability of system simulation programs as the commissioning tool. Analyses on the calculation results show that, though not a few differ-

ences exist among programs on their algorithms and calculation conditions/assumptions, primary energy consumption can be fairly well commissioned, if parameters and characteristics of HVAC equipments, system and subsystems and their control algorithms could be well adjusted to meet actual operation status. This kind of comparative study has a great advantage to identify merits and demerits of each program as a commissioning tool and then, with the findings of unknown idea to the past program developer, works as a motive force to let them grow more and more in their calculation functions and increase user friendliness in order to popularize use of HVAC system simulation worldwide.

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