Supporting strategic design of workplace environments with case-based reasoning

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Supporting Strategic Design of Workplace Environments with Case-Based Reasoning

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for Shaun

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I Am, Because You Are.

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CHAPTER I

Introduction

Creating Workplace Cases

This chapter provides the background and context of this doctoral research, along with its goals and objectives. The particular focus of this investigation is the use of building performance evaluation and Case-Based Reasoning to support the design of workplace environments. It seeks to shed light on part of what many design professionals recognize is a critical issue facing their practices today, reducing risk through the acquisition, retention, and exchange of knowledge.

I.1 Research Focus

This doctoral research investigates the use of a specific artificial intelligence technique, Case-Based Reasoning [CBR], as a research and application tool for supporting environmental engineering analysis in the early stages of strategic workplace design.

The objectives are to:

- develop a knowledge model relevant to the strategic design of workplace environments, and
- demonstrate how this model could be implemented in a CBR system.

A knowledge model represents both the *problem space* and *problem-solver*. In this research the problem space is technical knowledge of workplace environments such as lighting, heating, ventilation, and acoustical performance. The problem-solver is the strategic designer who uses the performance of previous designs during briefing and conceptual design to improve the performance of new workplace environments. CBR systems provide instrumental support for the use of precedents in decision-making. This study proposes to combine the modeling of performance and CBR to provide a means of effectively acquiring and transferring knowledge to support early strategic design decision-making.

I.2. Improving Workplace Environments

Researchers frequently report that quality of workplace environments has a direct influence on the productivity and effectiveness of office workers. Yet surprisingly, the most common work-related complaints of office workers continue to be about workplace environmental problems such as poor thermal comfort, air quality and acoustics. It is estimated that between 20-30% of existing building stock in Europe and North America are "problem buildings" (Bluyssen, Cox, Drunen, & Van, 1992).

This problem is likely to get worse rather than better in the future. The majority of workplace design and layouts have remained unchanged for decades, even though both the nature of office work and the worker have changed considerably. Currently, organizations are constantly re-sizing, automation is increasing and highly paid "gold-collar" office workers are replacing their clerical predecessors. As a result, there is increasing divergence between what a workplace environment should be and what the majority of offices are actually like (Duffy, Laing, & Crisp, 1993).

Increasing global competition, a greater awareness of health risks, and more stringent health and safety regulations will make it costly to ignore the impact that design and management of workplace environments have on individual performance and organizational effectiveness (Aronoff & Kaplan, 1995). Given the amount spent on salaries and facilities, the cost of improving workplace environments can easily be recouped by even a small increase in worker productivity. Jacqueline Vischer (1989) estimates that every $1 investment in building improvement results in a $10 return from improved worker performance. This being the case, why is it that so many office buildings have poor quality environments?

Antoineta Mendivil (1995) suggests that the area of technical design stands out as one of particular weakness for architects. My experience in teaching and practice suggests that part of the problem is that existing design methods and tools commonly available to many architects are inadequate or inaccurate for evaluating technical performance, particularly during conceptual design.

Conceptual design is the very earliest stage of design during which the main tasks are analyzing the problem and forming initial commitments towards a solution. As Domeschek, Kolodner and Zimring (1994) correctly point out, despite being a loose and informal process, conceptual design has a surprisingly "disproportionate impact on the ultimate cost and quality of a design artifact" (p.110). Technical decisions made at this stage are often based on information that is incorrect, incomplete (e.g., potential maintenance costs) or overly complex (e.g., code requirements) (Groot, Mallory-Hill, Zutphen, & Vries, 1999). Because many architects lack the tools and the technical know-how for evaluating environmental system issues at the conceptual design stage, engineers are left to face them at later stages of the design process when options are limited and changes are costly to make.

A growing awareness of this problem has encouraged some researchers to introduce new design methods aimed at improving the quality of early design decision-making, and as a result, decrease risk and make better fit between people and buildings.

Strategic Building Performance Planning & Evaluation [SBPPE] is a theoretical approach for undertaking briefing and conceptual design tasks being developed at the Eindhoven University of Technology [TU/e] in the Netherlands. This approach involves evaluating, early on in the design process, the potential consequences of office building design decisions according to strategic performance demand criteria, called "value-drivers" (Rutten, 1996). (See Chapter II.) This approach can reduce risks and improve the quality of office building designs, but is difficult to implement in actual practice. The approach requires the evaluation of conceptual designs (often sketchy and incomplete) according to complex, inter-active, and interdisciplinary performance criteria. For many architects, the knowledge needed for this is either unavailable or difficult to acquire.

In order to make strategic design work, a convenient source of building performance knowledge and a tool to deliver it into the architect's design environment need to be found. This dissertation explores how to capture technical performance knowledge from buildings in-use. The research uses *Post-Occupancy Evaluation* [POE] and applies *Case-Based Reasoning* [CBR] techniques to create a tool for disseminating this knowledge to architects undertaking strategic design.

I.2.1. POE and Technical Knowledge

Post-Occupancy Evaluation is a conventional method evaluating the performance of a building design after it is in-use. POEs can be extremely valuable because much of what is learned about technical performance, such as the level of environmental comfort, is only determined after people actually use a building. Unfortunately, POEs, if they are done at all, are rarely carried out by architects, but by separate engineering or management consultants. As a result, the lessons learned from POEs often do not reach architects for consideration in their future work. Unaware of the problems, many architects continue to repeat the same mistakes.

Although architects tend not to undertake POEs themselves, I propose the transfer of expertise gained from investigations done by others through computers technology.

I.2.2. Supporting Design with Computers

Case-Based Reasoning is one of a number of artificial intelligence techniques used in "expert systems." Expert systems allow computers to mimic human problem-solving behaviour. Expert systems were first introduced as a form of computer-based design support in the late 70s and 80s to address the increasing complexity of design problems. A big advantage of a computerized "expert" is that it is portable, distributable, and available when needed.

Unfortunately, early expert systems never really lived up to their expectations to provide computer-based design support. One of the reasons for this failure is the lack of formal or theoretical knowledge associated with design. This lack makes it very difficult to capture knowledge in the form of rules, logic or first principles common in the rule-based or model-based reasoning expert system paradigms.

Compared to rule-based and model-based approaches, CBR is a relatively new paradigm in artificial intelligence. The origin of CBR is attributed to the cognitive scientists Roger Schank and Robert Abelson (1977) who observed that memories and patterns of previous situations (scripts or *cases*) play an important part in both human problem-solving and learning. Instead of solving each problem from scratch, a case-based reasoner solves new problems by adapting solutions used to solve old problems (Riesbeck & Schank 1989). By representing knowledge as cases, CBR provides a promising alternative for computer-based design support compared to more formal knowledge representation approaches.

The development of CBR systems for design is still in its infancy. The first CBR design systems, JULIA (Hinrichs, 1988) and CYCLOPS (Navinchandra, 1988) were introduced in 1988. JULIA designs menus and CYCLOPS aids landscape design. Since 1988, several more systems, mostly academic, have been developed for a variety of design activities, including architectural design. With the exception of ARCHIE (Domeshek & Kolodner, 1992), however, very few have been developed specifically to assist designers during conceptual design.

In general, CBR has supported designers when generating a new design solutions with the recall and reuse of relevant design experience (Maher, Balachandran, & Zhang, 1995). The level of computer-based support encompasses aiding recall only, assisting during design, through to totally automating the generation of new design solutions. In this research, I have chosen to focus on using CBR as a source of knowledge instead of generating solutions. That is, to seek to support designers in recalling relevant design experiences that are outside of their own domain of experience (i.e., the domain of environmental engineering). They can then acquire knowledge needed to anticipate technical problems early on in design processes.

I.3. Research Context

The research described in this book is one of several projects within the *Building Evaluation Program.* The Building Evaluation Program is a long-term research initiative of the Physical Aspects of the Built Environment Section [FAGO] of the Faculty of Architecture at the Eindhoven University of Technology [TU/e]. It is undertaken in collaboration with the Building Research section of the Netherlands Organization for Applied Scientific Research [TNO] and the Design Systems department of the TU/e.

Both FAGO and TNO focus on the physical phenomena that influence the indoor climate and comfort of occupants inside buildings. The Design Systems department of the TU/e uses its experience with various programming languages and tools to examine the nature of computer-based design support. Motivated by the desire to develop and support strategic performance-based design and evaluation to improve the quality of buildings, these groups work together to:

> *Examine all aspects of office building performance with the eventual goal of developing a "intelligent," interactive, and easy-to-use computer support system to check proposed designs and evaluate existing buildings (Hill, 1997 p.ii).*

During the course of my research engineering experts from FAGO and TNO provided expertise relating to the evaluation and interpretation of building environmental control systems. Researchers and programmers from the Design Systems department provided guidance in the development of CBR systems. Additional expertise and examples relating specifically to workplace environment design were provided by consultants from professional practices: DEGW, Building Use Studies, van Wagenberg Associates, Rijksgebouwendienst, and Twijnstra Gudde.

I.3. Research Goal and Objectives

The goal of the Building Evaluation Program is:

> *To create a comprehensive SBPPE design decision support system environment capable of providing feedback in the early stages of design about all aspects of building design performance.*

My preliminary "Definition Study" (Hill, 1997) was one of the first projects of the Building Evaluation Program. It focused on establishing the theoretical foundations for Strategic Building Performance Planning and Evaluation [SBPPE]. The study identified the potential (and existing) roles for intelligent computer tools within that domain.

During the Definition Study, it became obvious that developing a computer system to handle all aspects of strategic office building design was a long-term objective. It was well outside the scope of a single research project. The Program team decided to begin by concentrating specifically on supporting the conceptual design of workplace environments.

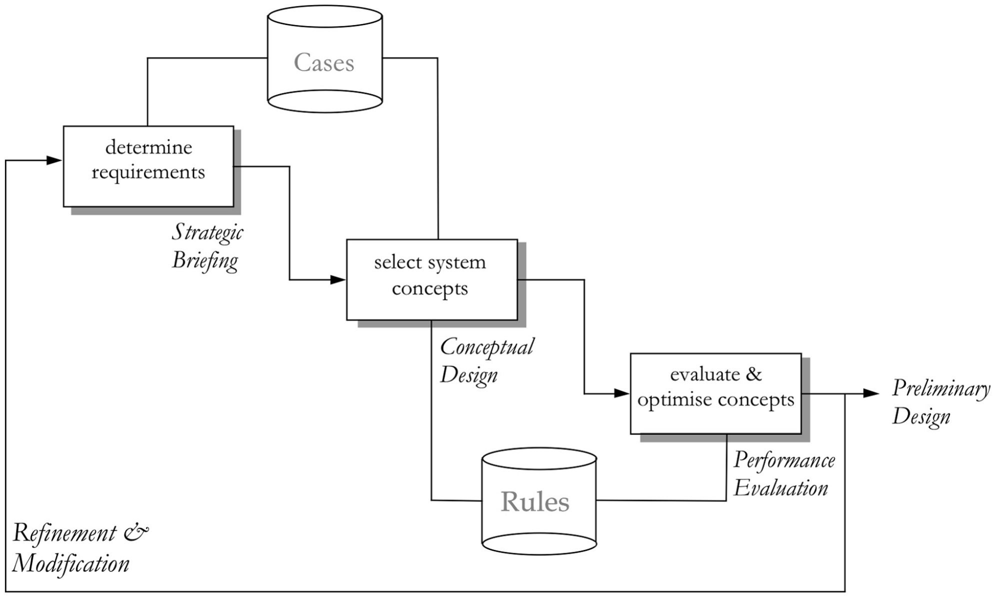


Figure 1.1. Simplified Support Model for Early Strategic Design Stages (Hill, 1997)

The support system model created in the Definition Study (shown in Figure 1.1.) identified opportunities for virtual reality, design agents, and two kinds of "expert" reasoning techniques (also known as Knowledge-Based Systems [KBS]) to support the strategic conceptual design process. (See also (Groot et al., 1999)). The first KBS technique provides evaluation of proposed workplace design concepts using technical expertise captured from human experts in the form of *rules*. The second provides assistance using the technical knowledge captured from existing buildings in the form of *cases*.

The Building Evaluation Program team decided to examine each of these techniques in more detail. This resulted in two doctoral projects. One examines the rule-based technique and the other, the case-base approach. The results of the study of the rule-based approach is described in (Groot, 1999) and the case-based approach is described herein.

The goal of my study is:

> *To determine the conceptual feasibility of using a Case Based Design Aid to disseminate technical knowledge acquired from POE to support designers during the early stages of design.*

My first objective, stated at the beginning of this chapter, was to develop conceptual knowledge models. Modelling is intended to facilitate the understanding of SBBPE, related tasks, and its support at a fundamental level.

The second objective involves the design and implementation of a prototype. Prototyping is intended to test out the underlying concept and provide a view of the approach to potential end-users.

Both doctoral projects have involved the creation of prototype systems. The protoypes: Integrated Lighting System Assistant or ILSA (Groot 1999) and Workplace Environment Design Assistant or WEDA (described in this book) contain expertise relating to the design of workplace environments. ILSA's expertise draws from domain experts and WEDA's expertise draws from POE of existing workplace cases.

The design and implementation of these small prototypes reveal the potential future of using KBS techniques to support strategic workplace environment design. They also are intended to provide an indication of whether or not the long-term goal of the Building Evaluation Program to create a comprehensive building design decision-support system can be satisfied.

I.4. Overview of Dissertation

This project combines reviews and analysis of relevant work published by others, knowledge modelling, POE and computer simulation of mock-up and real office environments, and prototype testing. The following provides an overview of the various chapters that discuss these topics in greater detail.

Chapter I has introduced this study, providing a general background and overview of this project, including its goals, objectives and key concepts.

Chapters II and III of this dissertation are devoted to fundamental issues. This includes a literature survey and establishment of the theoretical framework for strategic performance-based design [i.e. SBBPE approach] and CBR in design. Chapter II introduces a three dimensional conceptual framework for visualizing and organizing knowledge within the domain of SBBPE. The designer decision-maker's needs for effective knowledge support are identified. Chapter III reviews the history of CBR in design along with the examples of existing applications, before arriving at a statement in theory of a case-based design aid concept to provide knowledge support for workplace environment design.

Chapters IV through VII are dedicated to the development and feasibility concerns of supporting strategic workplace design with CBR. These chapters describe the development of the theoretical Case-Based Design Aiding system called *Workplace Environment Design Assistant* [WEDA].

Chapter IV introduces the conceptual models for WEDA. A process model is based on an examination of early design tasks and related instrumental support. Performance-based modelling of WEDA's expertise provides a way of connecting POE outcomes and early design goals. Chapter V looks at the problem of knowledge acquisition. A "toolkit" is developed for collecting and creating design cases based on the POE of actual workplaces. Chapter VI discusses the issue of control knowledge in a CBDA system. Control knowledge relates new problems to previous solutions. Two strategies for retrieving relevant workplace cases from a case-library are proposed. Chapter VII translates the theoretical and conceptual ideas of the previous stages into a practical perspective with a view on the nature of the intended user-system interface. A demonstration version of WEDA illustrates the operation of the system using the design example of visual comfort. Focus-group testing of the WEDA-demo provides feed-back on the potential future development of WEDA and systems like it.

The final chapter of this book summarizes the findings, identifies key lessons-learned, and suggests possible future directions for research.

CHAPTER II

Knowledge & Strategic Design

Total Quality Office Building Design

This chapter explores the particular importance of knowledge in strategic vs. conventional design processes. The lack of effective procedures for considering technical issues in the early design stages of office building design is a critical barrier to improving workplace quality. Emerging philosophies and techniques, such as Building Performance-Evaluation, Scenario-Buffering, Total Quality Management [TQM] and ISO 9000, encourage better knowledge reuse in the early stages of design. In particular, Post-Occupancy Evaluation [POE] is a key, yet undervalued source of knowledge for the architectural design process. These techniques are integrated into a model of strategic design for workplaces. Despite the advantages of strategic design, it demands coordination and access to vast amounts of multidisciplinary knowledge. This suggests a need for computer-based support.

II.1. Customer Satisfaction?

One can judge the success of current design practices by looking at how clients feel about the architectural products created. Unfortunately, the news is not good.

In *The Responsible Workplace*, authors Duffy, Laing and Crisp (1993) report an increasing divergence "between what people individually and collectively wish the workplace and office environment to be and what the majority of offices are actually like...."

In *Total Workplace Performance,* Stan Aronoff and Audrey Kaplan (1995) warn clients:

> "Since the office setting also affects human performance, its design and management impact the return realized from both salary and accommodation expenditures. In an era of global competition, every factor that influences workforce performance is a potential source of competitive advantage. An organization can ill afford to judge facility expenditures without an appreciation of the broad consequences of those decisions" (Aronoff & Kaplan, 1995).

The above statements suggest that many office buildings fail to meet performance requirements and organizations, aware that such failures are affecting productivity, are increasingly going to demand better guarantees of performance in order to gain or maintain competitive advantage.

Why do buildings so often fail to meet the expectations of their users? Aronoff and Kaplan (1995) suggest that some important issues contributing to overall workplace performance include:

- building systems
- thermal comfort
- air quality
- acoustics
- computers
- psychological factors, and
- individual control.

Problems in these areas suggest that many designers are not adequately addressing technical issues during design processes.

Researchers such as Antonietta Mendivil (1995) agree that the area of technical design stands out as one of particular concern in architecture. The lack of ability or "fluency" in dealing with technical issues means that the architect has to spend extra time to solve such problems, and this substantially increases project costs (ibid.). Instead, architects tend to rely on outside specialists, such as building engineers. When and how this technical expertise is included in design decision-making are critical.

II.2. Reducing Risk & Improving the Quality of Design

II.2.1. Current Practice

A traditional architect's procurement model, where the design professional provides "full services," can be described in terms of a "waterfall" of project stages (Figure 2.1). This process begins with the preparation of a requirement brief or "briefing" and progresses towards detailed design, construction and finally occupancy of the finished building.

Authors such as Tim Cornick (1991) and Charles Nelson (1996) suggest another model of design based on the business idea of "total quality management" [TQM]. Popularised during the 1980s and incorporated into ISO standard 9000, the basic principle of TQM is to reduce risk for the client. According to John Durkin (1994) risk involves "exposure to possible failure to obtain expected benefits" (p. 608). In order to reduce

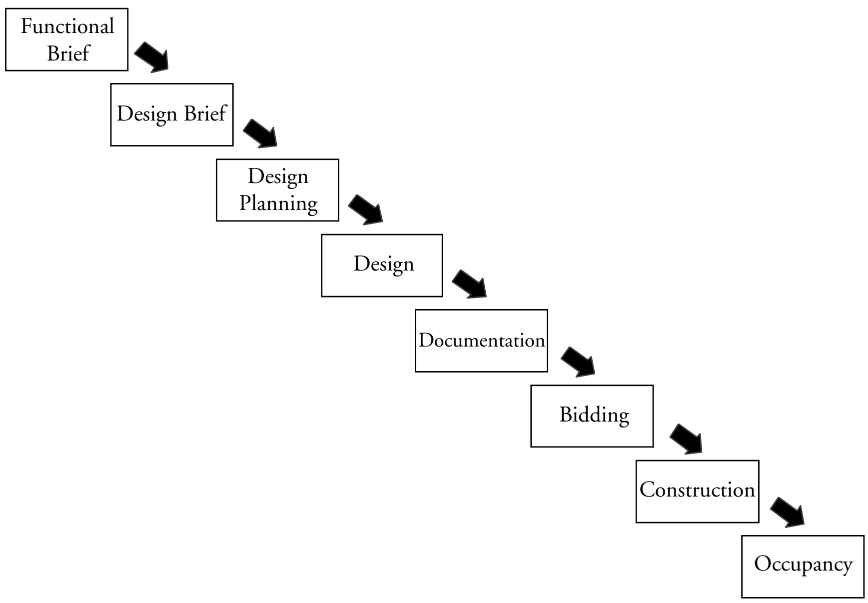


Figure 2.1. Traditional Procurement Model

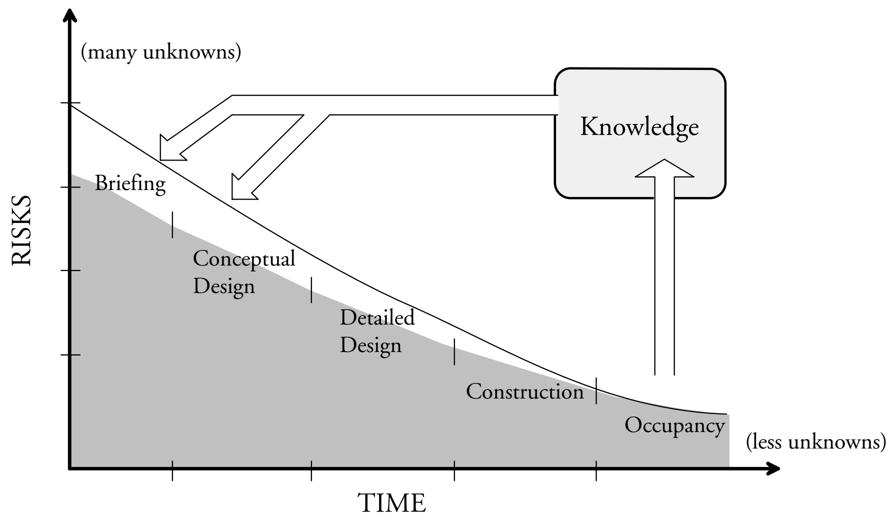


Figure 2.2. Reducing risk with knowledge feedback

risk, TQM emphasizes a need for constant improvement, and a reduction of uncertainty through a commitment to better documentation, evaluation, and feedback mechanisms.

Within the context of the entire lifecycle of a building, the client faces the highest level of risk at the beginning, simply because there are so many unknowns. Later in the design process, as more detailed information is known about a building, it is easier to predict accurately how it will perform. It should be possible to help reduce risk by conveying information and knowledge from the later stages back into the earlier stages of a design process (Figure 2.2.).

Nelson (1996) suggests that in the traditional building design procurement model many of the internal risk conditions (i.e. within the team and between stages) — for example inadequate briefing or inappropriate selection of materials — could be controlled by using better feedback mechanisms throughout the design process. Therefore, Nelson describes the procurement process not as a waterfall, but as a "feedback wheel" (Figure 2.3).

General knowledge transfer also needs to occur in the domain of the entire building industry. The design process diagram by environmental-behaviour researcher John Zeisel shown in Figure 2.4. explains the opportunities for feedback from research in the design cycle. Three primary areas include: (1) programming research (2) design review and (3) evaluation of built projects in-use (Zeisel, 1984).

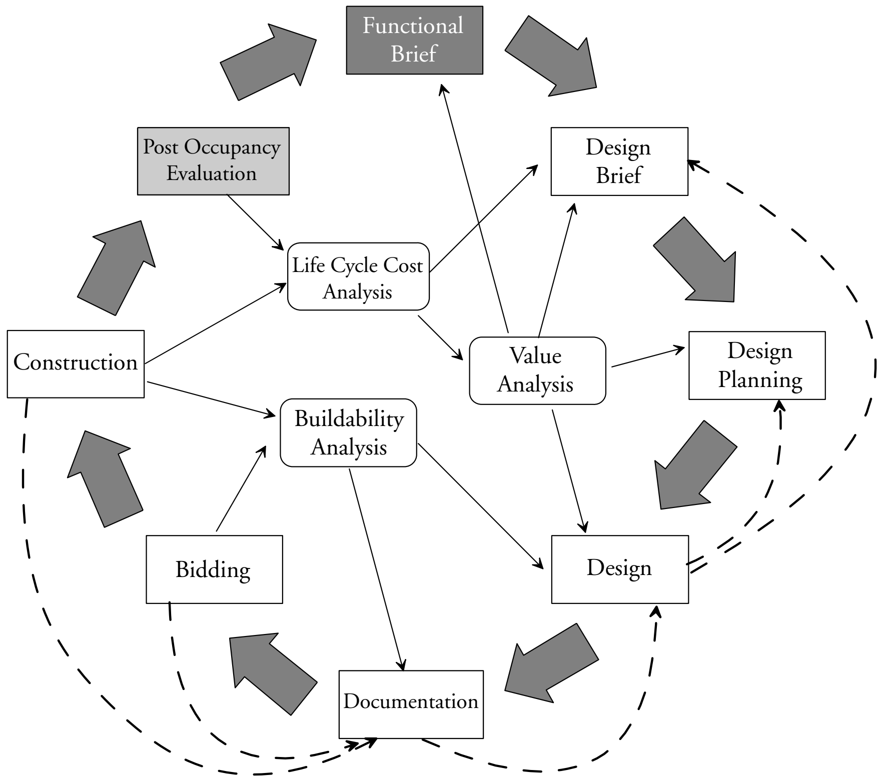


Figure 2.3. Traditional Procurement Model with Feedback Cycles (Nelson, 1996)

Both Zeisel's and Nelson's models demonstrate the importance of seeking opportunities to take what is learned inside and outside of the design process and incorporate it with what is already known, thereby advancing knowledge in a spiral fashion. This is what Nelson describes as 'the spiral of progress in quality' (Figure 2.5.): "What we learn from our experience can be measured by the pitch of the spiral. If it is very tight, we really

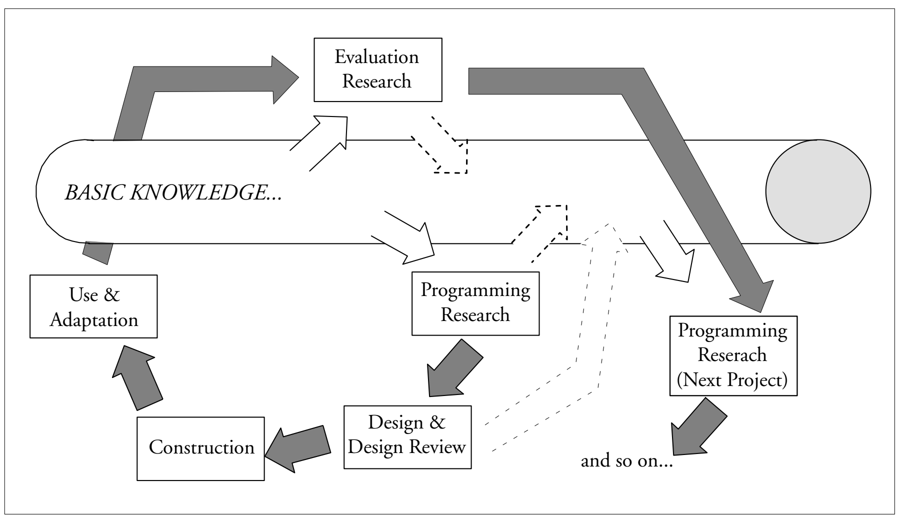


Figure 2.4. Feedback Loop (Zeisel, 1984)

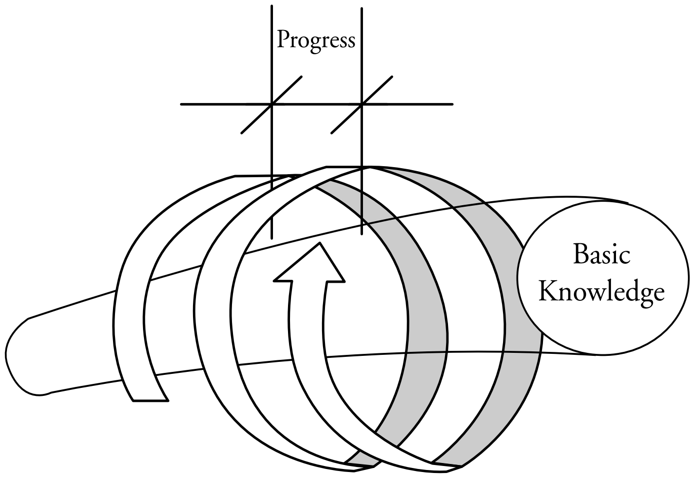


Figure 2.5. Spiral of progress

are only going in circles; if it is open, we have made progress as we went around" (Nelson, 1996).

II.2.2. Technical Feedback and Conceptual Design

The early design stages, briefing and conceptual design are often loose and informal processes. Yet decisions made at these stages can have a relatively large impact on the quality and cost of a final building (Domeshek, Kolodner, & Zimring, 1994). Early decisions constrain later ones.

Since technical decisions are often left for consultants address in later design stages, options can be limited to less suitable solutions because of earlier decisions — especially if earlier decisions were made based on non-technical criteria such as aesthetics, tradition or cost. The use of passive heating and lighting systems, which can save clients money, are particularly dependent on early design decisions about building site, form, orientation and even colour. Active HVAC systems, although independent to some extent from the external settings, do rely on appropriate floor space being set aside for equipment.

It would appear that providing architects with a good source of technical feedback at the earliest stages of design is very important if researchers like myself hope to improve the quality of workplace environments.

II.2.3. Sources of Technical Feedback

Experience shows us that during conceptual design existing sources of technical feedback available to architects within their immediate design environment are inadequate or inaccurate. These include:

- architectural journals and magazines
- archived project material
- site visits
- engineering analysis software.

Glossy architectural journals and magazines, although plentiful in most architectural firms, are a poor source of technical knowledge. Such magazines are badly indexed and technical analysis of the projects is often missing or incomplete. Occupant concerns seem to be a low priority since most of the time people do not even feature in the photographs.

Archived project material could potentially be a great source of corporate knowledge if it was accessible and complete. However, it is usually stored off-site given the volume of documents accumulated during a project. Since the relationship between architect and building usually ends when the building is occupied, this material concentrates on design solutions and not technical performance.

Sometimes an architect is lucky enough to be able to visit buildings relevant to the one they have been contracted to design. Normally considered a luxury, such visits tend not to yield knowledge about technical performance, because many architects may lack the in-depth engineering expertise and resources to interpret their observations of the building.

Designed by and for the use of engineers, evaluation tools such as RADIANCE (for lighting evaluation) or ESP-r (for performance measures such as the energy efficiency of integrated building systems) are a source of technical feedback. Although very powerful, these evaluation tools are also very complex and require special training to use properly. Moreover, such tools do not evaluate vague and incomplete conceptual design information. The feedback based on conceptual design input (requiring the heavy use of default values) will inevitably be inaccurate.

II.2.4. The Missing Link

The quality of technical aspects of building environments is most obvious at the last stage of the design process, once a building is in-use. This is primarily because many technical issues, such as energy efficiency or comfort, can only be accurately assessed after people use a building.

Post-Occupancy Evaluation [POE] is the formal measurement and interpretation of the successes and failures of building-in-use. POE contributes to the specific knowledge about solutions to particular problems (e.g., using indirect lighting to avoid glare on computer screens) as well as general knowledge about a design type or strategy (e.g., "flexible workspace"). This makes POE an ideal source of technical feedback not only for the owner of an evaluated building, but also for architects to improve the design of future buildings. This is why Nelson's feedback wheel (Figure 2.3.) shows POE flowing into the briefing stage of the next design cycle — providing a critical connection between each loop in the spiral of quality improvement.

Many architects, however, do not seem to take advantage of this obvious resource. The connection between early design and POE continues to be the weakest link in the design cycle (Figure 2.6.). Indeed, in the "waterfall" model of architectural design introduced earlier in this chapter the post-occupancy stage of design is completely missing. As Nelson (1996) observes, "the failure of all parties to recognize the importance of POE means that no provision is made by anyone to provide for the collection or analysis of POE data."

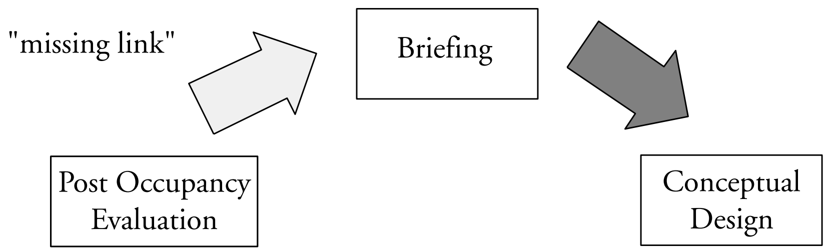


Figure 2.6. The Missing Link?

POE continues for the most part to take place outside the building design cycle. When technical problems occur with existing buildings, instead of turning to the original architects of the building, many owners will hire separate private consultants to evaluate and suggest solutions. The lessons learned from such private investigations generally do not reach the building industry. POE results about office building environments are published it is in sources targeted at building engineers, as in the case of the PROBE studies (Leaman, 1997; UBT, 2004) in Building Services Journal. The lack of integration of POE with architectural design practice means that architects are not able to access and incorporate this experience and knowledge into

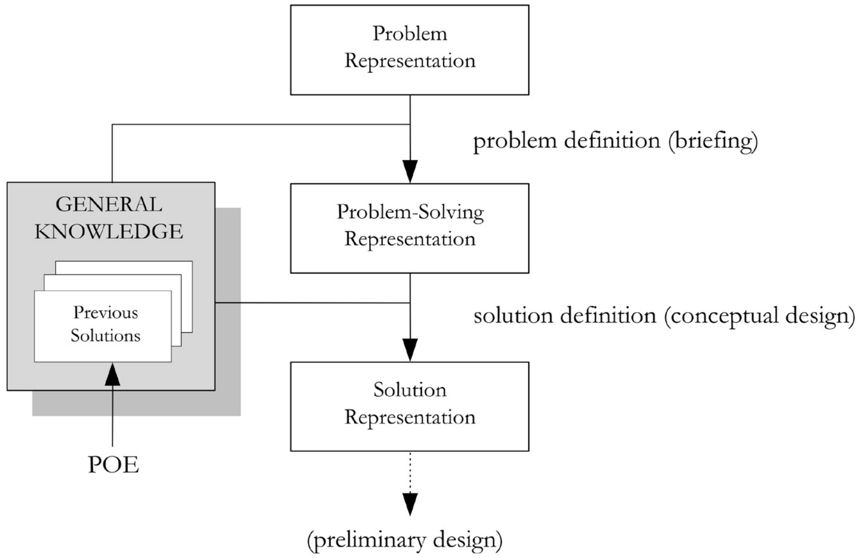


Figure 2.7. Knowledge Re-Use in Early Design Tasks

their decision-making process. We should not be surprised then, when the same problems occur again and again.

The following section introduces a design model that incorporates the feedback mechanisms necessary to improve technical design decision-making for architects. A critical aspect of this design model is a strong link between POE and early design decision-making (Figure 2.7).

II.3. Strategic Building Performance Planning & Evaluation

Strategic Building Performance Planning and Evaluation [SBPPE] (Hill, 1997) offers a theoretical approach to improve briefing and conceptual design decision-making for office building projects. SBPPE maximizes feedback mechanisms in order to minimize client risk as much as possible. The SBPPE model provides a basis for research in design decision support system applications in the areas of: (1) user requirement analysis (2) performance requirement definitionand (3) conceptual design and evaluation.

The following sections provide an overview of the theoretical background of SBPPE and its components.

II.3.1. Theoretical Basis of SBPPE

SBPPE is a combination of two philosophies:

1) Strategic Facilities Planning (Brand, 1994)
2) Building Performance Concept (Ware, 1972) (Wright, 1972) (Davis & Ventre, 1990; Preiser, Rabinowitz, & White, 1988b; Preiser & Schraam, 1997)

Both methodologies are closely tied to TQM techniques and ISO 9000 standards.

Strategic facilities planning is a requirement analysis technique. Rather than concentrate only on defining the immediate needs of a client, strategic planning suggests architects need to take a longer view. It suggests buildings must respond to change over their entire lifecycle. Strategic planners use a highly participatory process to anticipate the range of stakeholder demands for any given building Subsection II. 3.2.1. explains this process in more detail.

The Building Performance Concept is a method for representing and evaluating buildings. This systems-based approach defines buildings and their sub-systems in terms of performance or functional terms only; it includes tests to measure performance as well as a clear statement of subsystem interfacing. Stakeholder's needs define the acceptable limits and ideal states of system performance for each building.

Performance evaluation (the comparison of the match between demand criteria with design performance) along with recommendations for improvement, forms the basis of feedback about a building's design (or design type such as "office building") (Preiser, Rabinowitz, & White, 1988a). Designers who use the performance concept to guide their decision-making make rigorous use of evaluation and feedback to assess past successes and failures. Subsection II.3.2.2. explains these ideas further.

II.3.2. SBPPE Model

With the SBPPE approach, even at the early design stages, it should be possible to distinguish between functional and dysfunctional design concepts. In this way unsatisfactory designs can be eliminated at the conceptual stage before more effort is given to develop them and changes are difficult to make. Furthermore, it is important to use all relevant criteria that impact on quality to judge acceptability. This can be especially challenging when criteria comes from a field outside the experience of the decision-maker.

This is why a strategic performance-based approach requires a high level of stakeholder participation and cross-disciplinary feedback.

SBPPE encompasses four main procedures:

1) strategic facility planning
2) requirement & performance modelling
3) performance evaluation
4) repair & refinement.

The first procedure concerns adequate requirement analysis and definition of building requirements (demand analysis). The second entails the representation of building design concepts and client requirements. The third compares requirements against building design performance (Griffith & Domeshek, 1996). The final procedure adjusts a building design and/or requirements to ensure an optimal match.

II.3.2.1. Strategic Facility Briefing

> *In practice many a thoroughly programmed building is obsolete by the time it is built (Brand, 1994).*

Successful businesses have learned through strategic planning how to learn from their experiences, to be flexible and adaptable to deal with uncertain futures. Authors such as Adrian Leaman, William Bordass (1995) and Stuart Brand (1994) suggest that a similar approach can be used for the design of buildings as well.

Traditional building briefs are usually based on detailed analysis of the current client needs based on common practices. Such briefs contain actions to be taken now to prepare for the future. More often than not, however, predictions of the future are misguided.

A good strategy should provide the flexibility to accommodate an unpredictable future (Figure 2.8.). Strategic or scenario planning reaches into a future where many potential paths may be taken. As with conventional facility programming, scenario-buffered briefing involves a formal process of analysis and decision-making, but it is much more divergent in its approach (Brand, 1994).

Strategic briefing begins with clarifying a vision for success, but not necessarily the means for achieving that success. Over the briefing process, and even after the building is in-use, the vision acts as a compass to judge if

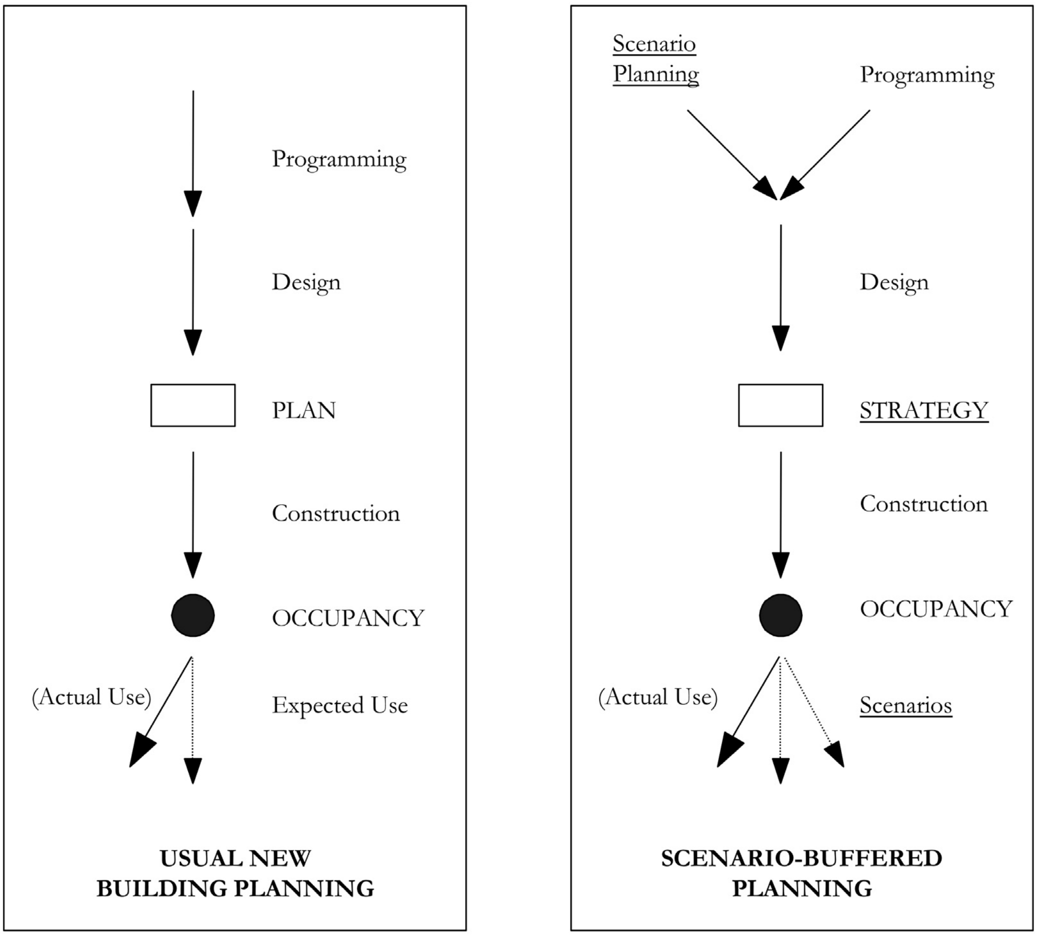


Figure 2.8. Scenario-Buffered Planning (Brand, 1994)

things are going in the right direction without getting bogged down in the details of how to get there.

In a strategic facility briefing process, project stakeholders and policy-makers link organizational goals with those of real estate, design and capital development policy programs and objectives (Cameron, Duckworth, Kresiel, & Siroskey, 1997). This involves discussions about the anticipated future (e.g., "Everyone will work in teams together") and creatively brainstorming about possible alternatives to that future (e.g.,"Everyone will work at home with computers" or "Employees will spend time working at different offices").

Uncontrollable forces impact on the future environment in which goals need to be achieved and also need to be taken into account. These are most often related to what are known as PEST risk factors (ICMBA, 2004) — Political, Economic, Sociological or Technological changes. For example: "If the cost of energy goes up and the use of computer technology increases, this office building will have high cooling requirements and high operating costs."

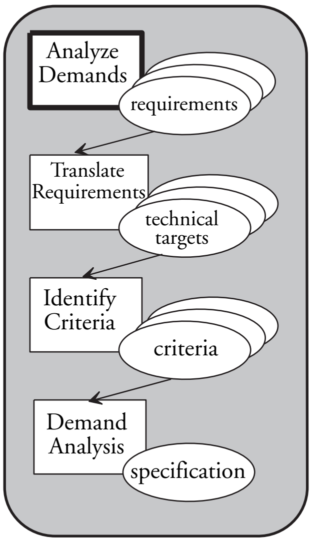


Figure 2.9. Strategic Briefing Task Model

A model for the basic tasks of strategic briefing is proposed in Figure 2.9.. During strategic briefing, two to five future scenarios typically establish the scope of stakeholder requirements. The building is treated as a strategy, as a package of options and activities, and judged on its ability to perform under a variety of scenario conditions (Brand, 1994). Scenarios generated during strategic briefing define the upper and lower levels of building performance required. Demands are usually expressed in ranges of performance instead of absolute values (Figure 2.10.).

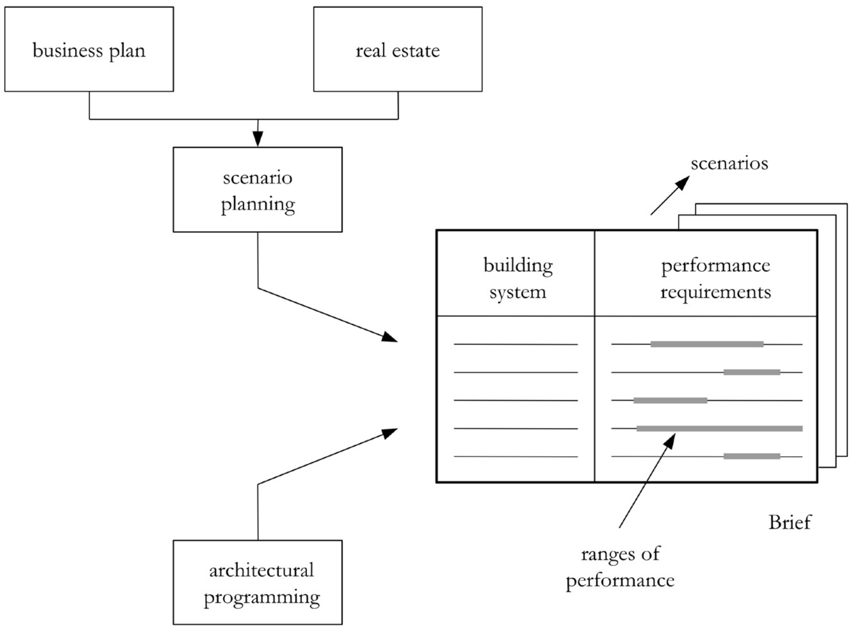


Figure 2.10. Inputs to Brief

II.3.2.2. Requirement & Performance Modelling

Once the key stakeholders requirements have been determined through strategic briefing, the next steps are to represent those demands in an architectural specification and respond to those demands with conceptual design solutions. To represent both "demand" and "supply" so that they can easily be compared, SBPPE uses the Building Performance Concept approach

The primary goal of "Building Performance Concept," sometimes referred to as "Total Building Performance," is described by Ware (1972) as "the assurance of desired performance delivered to building users" (p. 362). See also (Wright, 1972) and (Davis et al., 1990). The Building Performance Concept works by providing a flexible and organized (systems-based) procedure for description and evaluation. During this procedure, both stakeholder goals and conceptual designs are described in performance rather than prescriptive terms, allowing for easy comparison.

The building performance approach can be used at many different stages of the design process — from briefing and conceptual design to detailed, or even post-occupancy evaluation. Generally speaking, the application of the Building Performance Concept to early design involves four main activities:

1) Transformation of stakeholder requirements into technical performance requirements and criteria,
2) Generation of conceptual design responses,
3) Transformation of conceptual designs into performance descriptions, and
4) Evaluation and selection of conceptual design.

The first two activities described above correspond to the strategic planning and architectural briefing stages of design in which the requirements of various stakeholders are analyzed. The outcome of this is a "demand model" or performance requirement brief. The last two activities correspond to conceptual design in which initial solutions are generated and then represented as a "supply model" or performance description.

Performance Briefs

The performance-based approach to briefing is most easily understood when it is contrasted with the conventional practice of creating prescriptive requirements or specifications. Prescriptive approaches typically concentrate on elements such as the type and quality of materials, method of construction, and workmanship. While generally easier to specify, these "recipe" specifications can may inhibit a more innovative and efficient solution. A performance-based approach encourages a high degree of problem definition while still encouraging many solutions. In a performance specification:

- human needs are captured in the form of declarative statements: (functional) performance requirements,
- statements are quantified into (requirement) performance criteria or indices (usually a numerical representation/range based on a relevant measure), and
- performance evaluations or tests are stated (physical, simulation, judged by experts) for determining if solutions meet the criteria. (Ware, 1972).

According to Nelson (1996) advantages to using a performance-based specification include:

- lowest price — allows contractors to be more competitive since they are not restricted to one system but can create their own solutions as long as performance targets are met,
- time — construction time is reduced since contractors can choose from locally available components,
- risk — the responsibility for design and execution is centralized, and
- knowledge — if a designer lacks enough knowledge to write a good prescriptive specification (methods, materials, products, and so on will only be as up-to-date and appropriate as the specification writer's knowledge permits), the contractor can use their specialized experience to pick a suitable solution and match the desired performance.

It is important to note that, at least in North America, writing a performance specification does not free the architect of the legal responsibility for guaranteeing that a solution proposed by a (sub)contractor or supplier will in fact meet the performance requirements. In the end, it is the architect who is responsible for ensuring the completed design meets design requirements. It is for this reason that architects may have to know more about a system than if they had written a prescriptive specification (Nelson, 1996).

This underscores the need for architects to be able to acquire and apply technical knowledge. Although a performance-based approach can facilitate

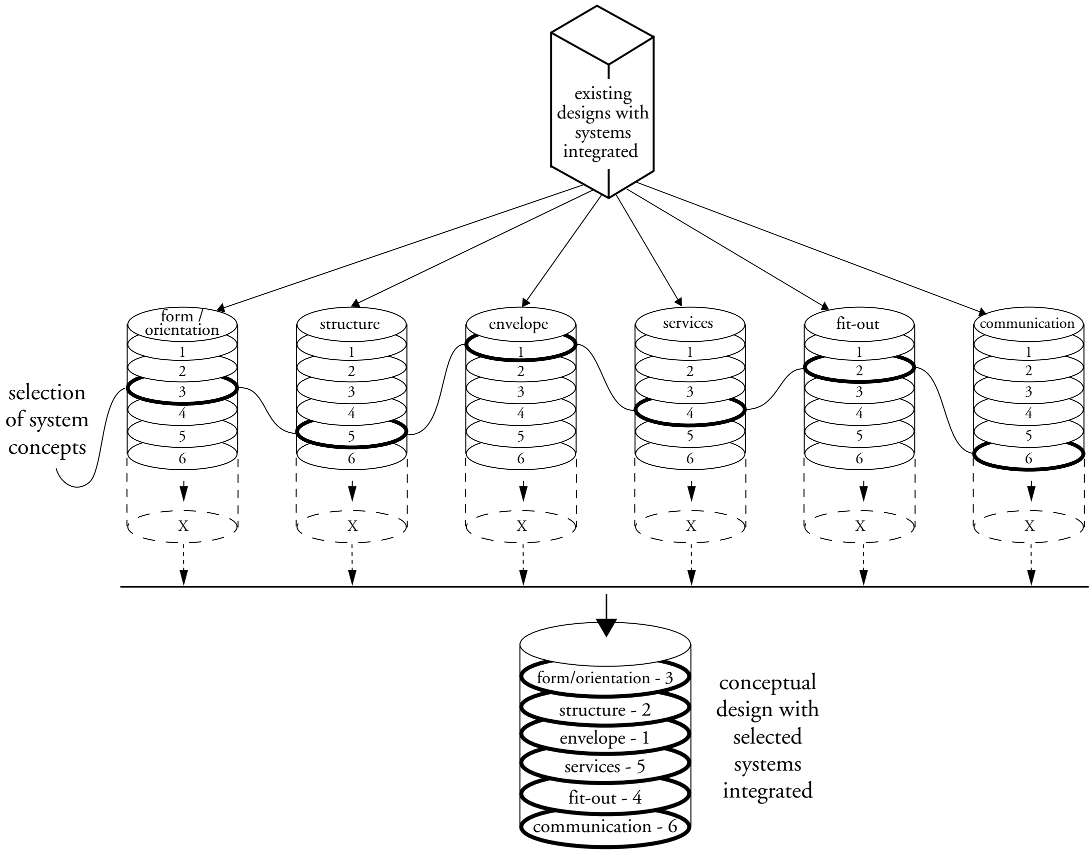


Figure 2.11. Selecting System Concept Models

communication between disciplines, it is not a replacement for adequate technical education and training.

Concept Performance Modelling

Once a number of design concepts have been generated by the designer, the next step is to model their performance. The goal of performance modelling is to create a representation of conceptual building strategies (for various building elements and systems) and the behaviour of those systems. This means relating building-types and their (sub)system concepts to performance descriptions (see Figure 2.11.). Whereas the performance specification is a model of "demand," the conceptual design performance description is a model of "supply."

Rather than dividing the building amongst various domains of expertise (e.g. architecture, engineering, management...etc.), each building-type (in this case "office building") is divided into six to ten sub-system concepts. Each sub-system provides a discrete and major element of a finished building. The different sub-system or Building Systems Levels [BSL] I use are based on (Brand, 1994) (See also sub-Section II.4.2.)

Each combination of subsystems (i.e., the conceptual design model) needs to describe how that component behaves, its relationship with other components, as well as qualitative and/or quantitative simulations and tests (if known) for how to judge its performance.

Since a proposed conceptual (sub)system is not real, its actual performance cannot be measured. To describe how it would perform architects would need to rely on their experiences or a simulation tool. My study suggests deriving performance descriptions for conceptual designs by matching them to the post-occupancy performance evaluation of similar existing building designs. I describe this in more detail in Chapter IV - *Supporting Strategic Workplace Design*.

II.3.2.3. Performance Evaluation

Once a set of initial design concepts have been created, the final step in the SBPPE approach is to decide which concept to use and/or refine further. Building performance evaluation compares human needs ("demand") against what the building systems ("supply") are able to provide. This evaluation is usually done at a particular architectural scale (e.g., building, workplace or workstation). The best solution is not the one with the optimal performance, but rather the one that has most closely matches demands with performances.

Figure 2.12. offers a fictional example of a performance-based design decision regarding a lighting system. Here a set of performance requirements are compared with the performance of three lighting design alternatives. Performance briefing provides the various demand criteria (C_1, C_2, C_3…. C_x), conceptual design generates a number of alternatives (A_1, A_2,…A_x),

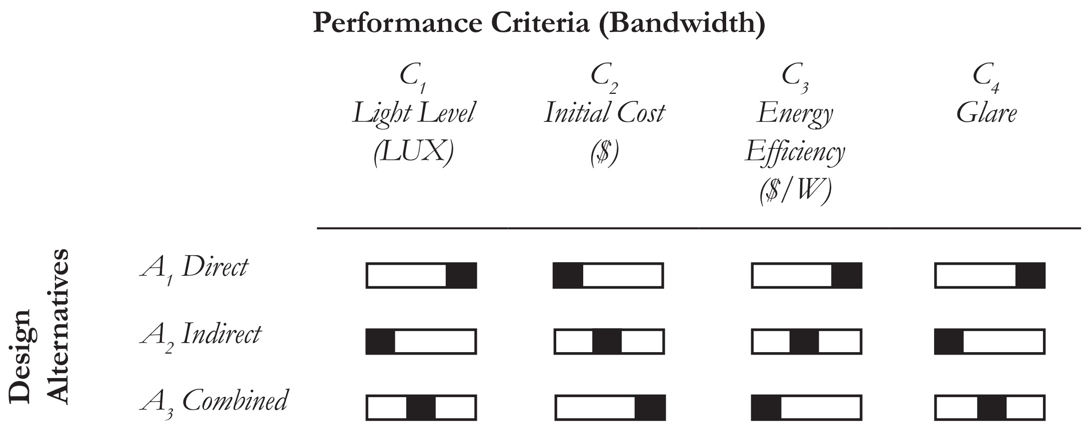


Figure 2.12. Fictional example of performance-based design evaluation.

and performance modelling of the conceptual design alternatives predict the level of performance (shown here as low, medium, high in bandwidths). Figure 2.12. shows how the decision to use an indirect/direct lighting system will have the best energy savings, but also have a high initial cost.

II.3.2.4. Evaluation Feedback, Repair & Refinement

There are potentially an infinite number of issues to consider in any building design problem. Even if it were possible to consider all of them, would designers want to, particularly at the early stages of design?

Simms and Becker (1990) suggest that an important first step is to identify the key areas in which concerns, if dealt with properly, will minimize risk and maximize quality. According to a CIB report on working with the

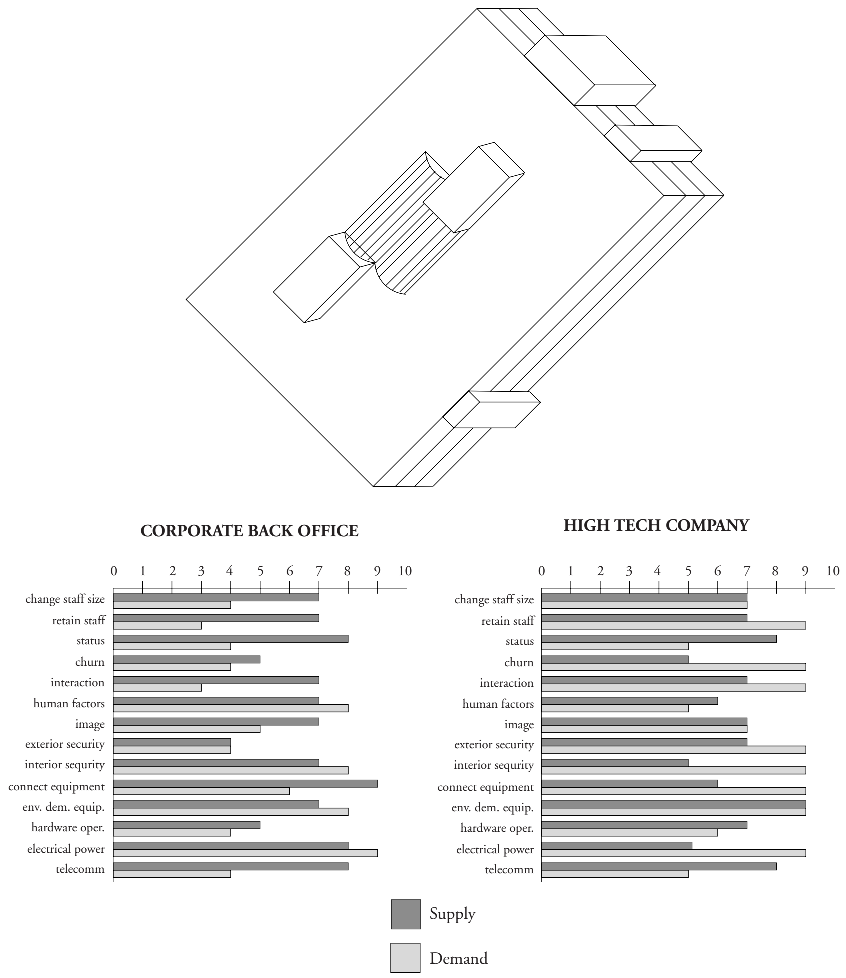


Figure 2.13. Performance Profiles (Simms & Becker, 1990)

Performance Concept, the number of performance indicators or attributes that one can reasonably and rapidly evaluate in detail is limited — somewhere between 14 and 25 attributes (Keeble, 1982).

In creating ORBIT-2, a facilities evaluation tool, Simms and Becker (1990) show how it is possible to provide meaningful feedback about office building performance using only fourteen criteria. The beauty of their approach lies in the use of simple comparative indices, or performance profiles, which quickly reveal any deficiencies or excesses in how a building meets key client requirements (see Figure 2.13.).

The feedback from such sets of criteria evaluations makes it possible to compare different strategies and their cost-effectiveness tp improve the building's overall performance rating. Once identified, such shortcomings can be addressed with repair or modification of a selected concept, the final cycle of SBPPE (and conceptual design) processes — refinement (Figure 2.14.).

In my study, I have concentrated on identifying the key performance indicators relating to human comfort in the workplace. This is explained in further detail in Section II.5. To better understand how these criteria

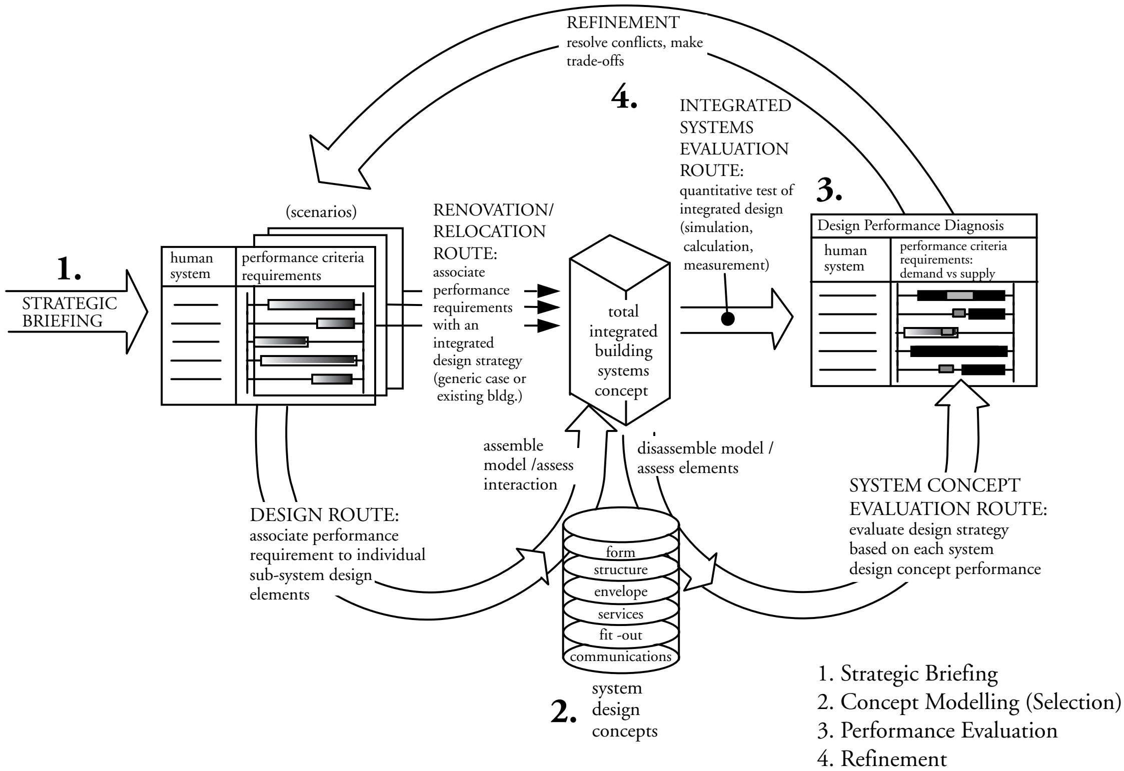


Figure 2.14. Strategic Building Planning & Evaluation Process

relate to other building performance criteria, I will first introduce a general domain knowledge model for office building evaluation.

II.4. SBPPE Domain Knowledge Model

Part of the on-going research and development of SBPPE is to identify and evaluate design criteria relevant in early design of office buildings. Design criteria come from many different domains, such as architecture, environmental engineering, facility management, and interior design.

To provide a means of visualizing the complexity of performance measures a general ordering model was needed, a model of the Building Performance Evaluation Domain. The 3D Domain Model created in my study is shown in Figure 2.15 (Hill, 1997). The Model includes three different axes:

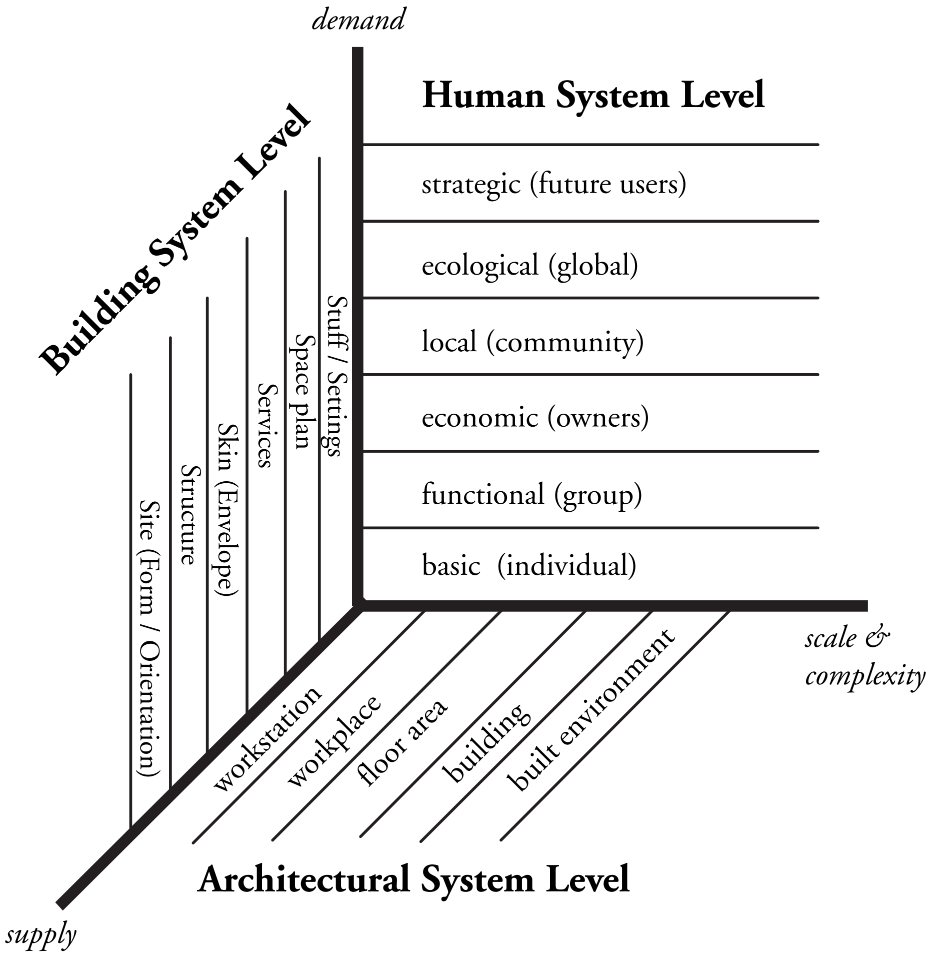


Figure 2.15. Building Evaluation Domain Model

1) Human Systems (6 Levels)
2) Building Systems (6 Levels)
3) Architectural Scale (5 Levels)

The Model was inspired by David Lantrip's "Total Environmental Performance Model" ((1988) in (Wise, 1990)) which shows increasing scalar dimensions and combinations of human-environment interactions at various performance levels. The addition of Building System Levels expands Lantrip's original model to include building elements. This allows the new Model to illustrate that facility performance measures are relevant to both user requirements and building behaviour.

Projection of the Model's levels generates 180 cubes, each representing a sub-domain of investigation within the total domain of building science. Each cube is further divided into a number of sub-fields of knowledge. The part of the model relevant to my study is elaborated in Section II.5.

II.4.1. Human System Levels [HSLs]

An office building derives its total value based on the quality of its relationship with its human environment. Although not necessarily mutually exclusive, the interests of different "users" of a building can be quite varied — from a person who works in it daily to a student who studies the design in a distant classroom. The overall value of a building derives from how well it performs at all of the various human perspectives from which it is viewed. For example, the Sydney Opera House derives its high overall value from its performance at many levels: as an international symbol of Australia, a tourist attraction, an engineering wonder, and as a performing arts centre.

Defining total building quality therefore requires that the needs of all potential stakeholders be considered. Who are these stakeholders? What are their requirements likely to be?

Six categories of stakeholders or Human System Levels [HSL] are used in the SBPPE model:

- individual occupants
- organization & groups
- owners
- community
- global community
- future users & contexts.

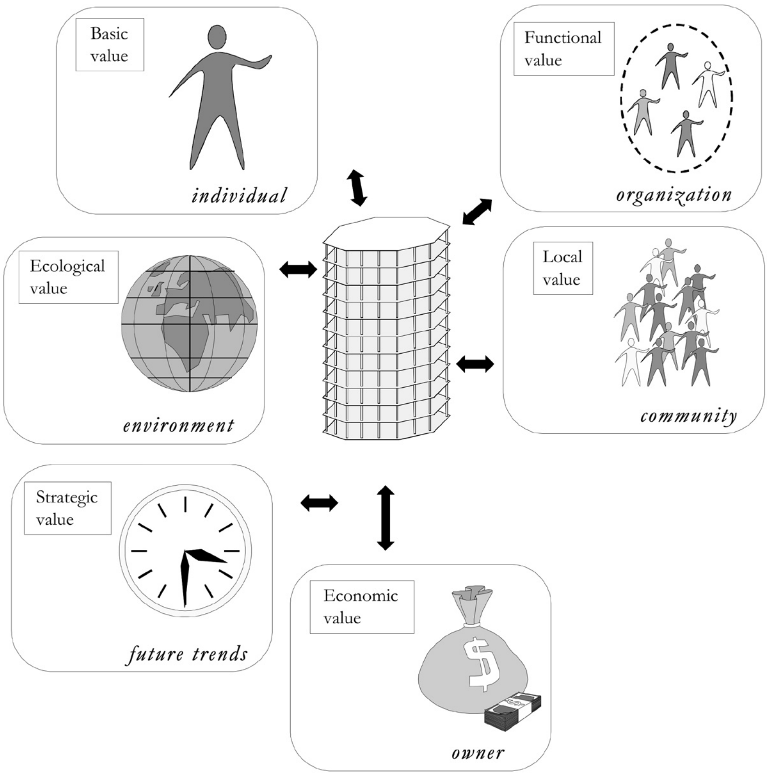


Figure 2.16. Human System Levels (Hill 1997)

A performance specification describes performance goals for each human-building relationship. For each HSL, the building needs to behave in a certain way. This is considered the "goal" for the relationship. Strategic goals for performance are attributed to each HSL (Figure 2.16.). Paul Rutten (1996) suggests that by considering the combined performance of top-level requirements — the so-called 'value-drivers'— one can determine a building's total value. To elaborate on what a HSL might consist of, each was defined in more detail in this study through analysis of domain literature and comparison with Rutten's original value-driver concept.

Basic value (Individual) is determined from a building's relationship with individual occupants and their sense of psychological and physical well-being. Requirements under this category include: building integrity, spatial comfort, acoustic comfort (control of building and office noise), visual comfort, thermal comfort, and air quality.

Functional value (Organization) is concerned with how activities taking place inside the building are supported. Underlying requirements include:

support for production, manageability, operations & maintenance, and cleanliness.

Economic value (Owner) is based on the relationship with people concerned with the ownership and marketing of the building. Sub-level requirements include: initial cost, life-cycle costs (operating costs & maintenance costs) and demolition costs.

Local value (Community) is based on special conditions that are unique to a particular place; anything that may prevent a building from being constructed in the most straightforward way. This includes the need to respond to earthquake zones, extreme climates, building regulations, or historical contexts.

Ecological value (Global community) considers the relationship of the building to the global environment. Considerations include how a building uses resources (energy, materials & water), and/or creates waste and pollution.

Strategic value (Future users) is an abstract human-building relationship as it considers performance requirements associated with time and the future. This includes the ease with which a building accommodates the needs of many different occupants and occupancies (universality) and/or how it can be adapted or modified over time to fit (changeability).

II.4.2. Building System Levels [BSLs]

Building systems supply the performance intended to satisfy client demands. The Building Evaluation Model contains six building system levels [BSLs] based on Stuart Brand's "six S's" (1994) as shown in Figure 2.17.. Brand's building system categories account for how often change occurs — from very often to rarely:

- stuff (furnishings and equipment)
- space-plan (floor plan)
- services (HVAC, lighting, acoustics)
- skin (envelope)
- structure (skeleton)
- site (form and orientation)

These categorizations of building systems are Group level entities. Each Group level can be further divided into several sub-system components. For example: Services can be further divided into: (1) security (2) lighting (3) energy (4) air-regulating (5) sewage, and (6) conveyance systems.

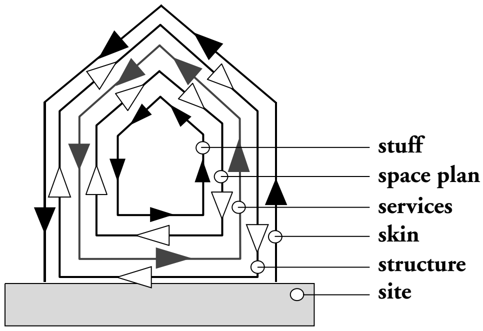


Figure 2.16. Layers of Building Change (Brand, 1994)

II.4.3. Architectural System Levels [ASLs]

Architectural System Levels [ASLs] represent the level of architectural dimension or detail in which decision-making is taking place. For example, a designer can think about lighting in terms of an individual workstation or in terms of an entire building. In the Building Evaluation Model, office buildings are divided into six levels of scale: (1) work station, (2) workplace, (3) floor area, (4) building, and (5) built-environment (Figure 2.18.).

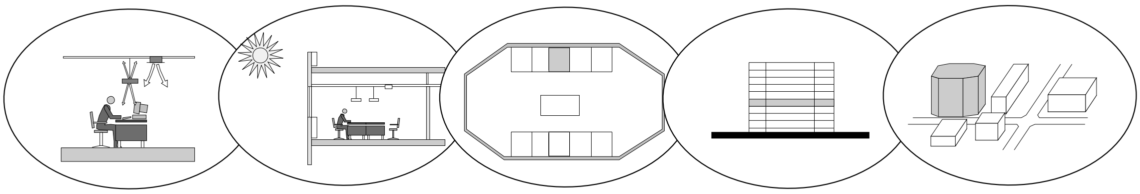


Figure 2.18. Architectural System Levels derived from Rutten's (1996) "inside-out design" (p.28)

II.5. Knowledge & Strategic Workplace Environment Design

In theory, decision-making during a strategic performance-based building design process should encompass all the information contained within the 3-D domain model. But to acquire and model so much information on so many levels is well beyond the scope and resources of any single study. So after developing the Building Evaluation Domain Model, I chose to concentrate on elaborating knowledge within a single "cube" within the model, the cube relating to the design of workspace environments (see Figure 2.19.).

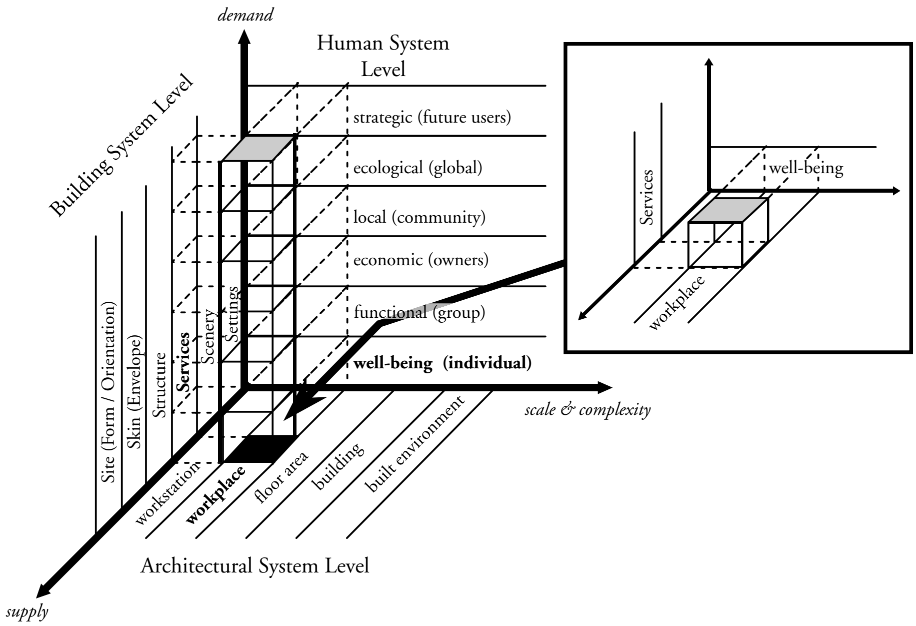


Figure 2.19. Indoor Evaluation at WorkplaceLevel

As described in the earlier, each intersection (or "cube") in the Building Evaluation Model represents the evaluation of an issue — a performance demand and a performance supply viewed at a particular architectural scale.

The evaluation of workplace environments is represented by the intersection of Basic Well-Being with Services at the Workplace level. For example, say an organization wishes to attract hi-tech, well-educated staff who are in limited supply. A good way to attract and, more importantly, retain employees is to create a comfortable workplace. The designer will need to judge if his or her proposed (or existing) building services concept can provide a sufficiently high level of comfort in the workplace.

Such an evaluation is quite complex because there are many sub-system levels (see Figure 2.19.). The well-being of an individual is fulfilled by many different requirements (e.g. safety, health, comfort, etc.) supplied by a variety of different inter-related building service systems (e.g., HVAC, lighting, etc.). At a certain architectural scale a number of workplace concepts may be considered as well (e.g., open plan, cellular, group work areas).

As part of this research, a survey of domain literature was undertaken to reveal the underlying subsystem levels in my selected cube and identify the nature and scope of the domain of workplace environmental performance. As a result of the literature survey, a list of possible (demand) requirements and (supply) elements facets that could impact on workplace environment performance were assembled. The facets were assembled into a "Knowledge

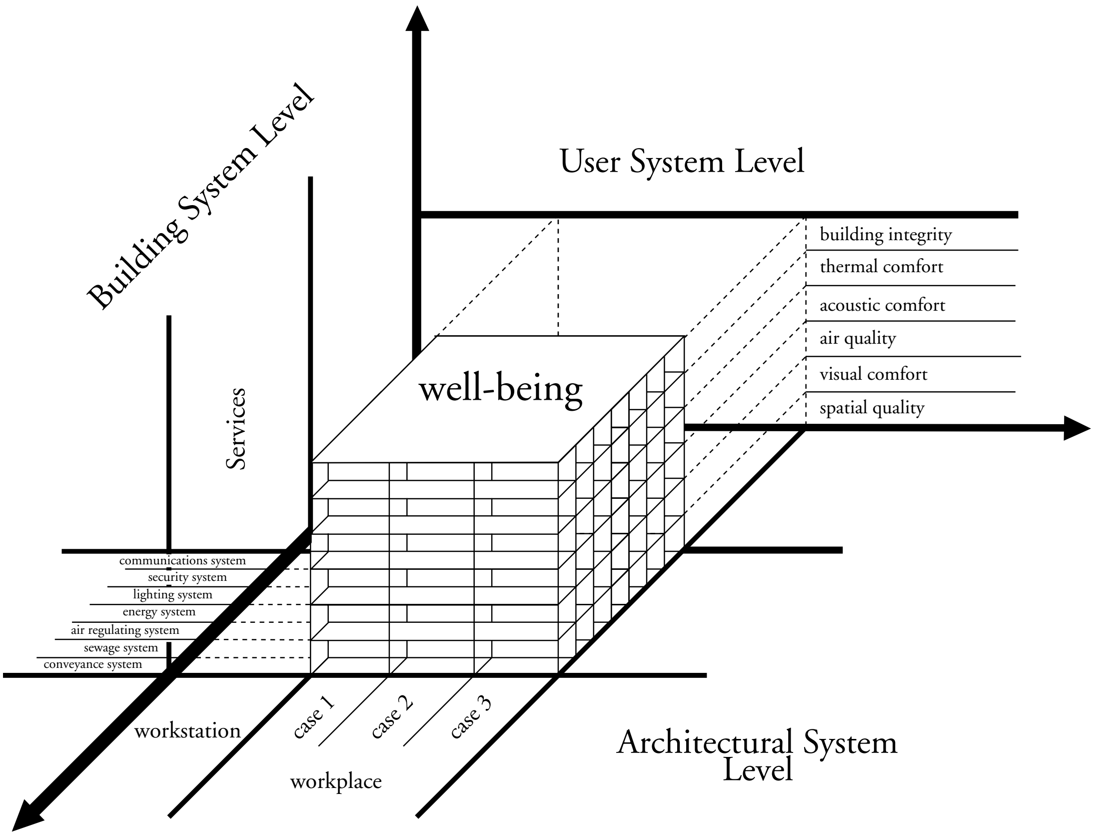


Figure 2.20. Performance Evaluation of "Well-Being" in the Workplace

Acquisition Model" to facilitate acquiring the knowledge relating to each of them. This acquisition model is described further in Chapter IV.

II.6. Barriers to using Strategic Methods of Design

SBPPE offers a new approach to early design that can help reduce risks and improve the quality workplace environments. However, some of the characteristics of SBPPE make it difficult to implement in practice. The key barriers to overcome relate to:

Performance Representation:
- requirement modelling
- performance modelling, and

Performance Evaluation:
- dispersed expertise
- volume of criteria
- multiple-criteria decision-making

Requirement Modelling. One key aspect of SBPPE design is to connect stakeholder demands and real estate goals. Once the stakeholder's demands have been determined through strategic briefing, the next step is to translate these demands, (e.g., "three secretaries using computers") into an architectural performance demand (e.g., "3 m^2 of floor space/person" or "next to entrance"). According to Mendivil (1995) while synthesizing solutions, many architects tend to "concentrate mainly on formal and functional performance, neglecting or even completely ignoring technical performance" (p. 38). How much light would three secretaries need? What kind of noise level would be acceptable? If they have neither experience nor training in analysis of such technical issues, an architect needs support to determine the engineering implications of stakeholder demands.

Performance Modelling. A large part of performance-based design like SBPPE relies on accurate representation and prediction of the performance of proposed conceptual designs. Conceptual architectural designs are vague and incomplete because they represent the idea of something (for example, "windows") rather than an actual instance (e.g., ACME#123 double-glazed sliding window). Architects, by convention, use sketches, bubble diagrams, and abstract models to make concrete their initial interpretation of both the design problem and its possible solution. Although such artefacts are an important part of early design development, they offer a poor basis for a detailed lighting analysis or energy audit. Another source of technical feedback is required.

Dispersed Expertise. A serious barrier to SBBPE is that expertise about a particular issue is unavailable and/or is dispersed over many disciplines. This makes it hard to move easily across levels of performance evaluation (Figure 2.20.). Critics suggest the building performance concept presupposes that one can describe scientifically what a building (or part of a building), will do, and how to assess its performance before and after construction and occupancy. Strategic briefing requires anticipating future organizational or occupant needs.

> "In actual practice designers lack sufficient knowledge of building science, the process of building element manufacture, cost control, design and assembly of buildings and their detailed maintenance and operations to make the judgements required to use the performance approach to building in its pure form" (Robbie, 1972).

That is not to say the knowledge does not exist, but rather that is in a form or place inaccessible to many architects. Architects need a means of easily accessing knowledge found in other domains.

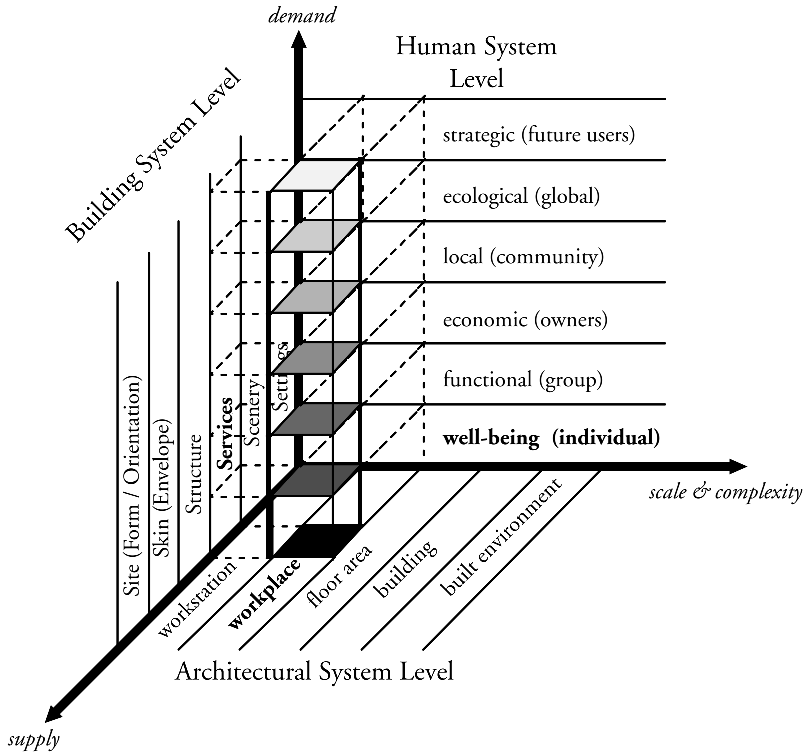


Figure 2.20. Knowledge Transfer between Levels

Volume of Criteria. In order to make the best decision possible, it is important to take all relevant criteria into consideration. As much as the Building Evaluation Model attempts to capture all building facets that should be evaluated, it may not be practical or even desireable to do such a complete evaluation. The more knowledge and information architects are able to draw upon, however, the better their decisions are likely to be. Therefore, an architect needs to have a support to store and recall as much relevant criteria as possible.

Multi-criteria decision-making. How do designers know if one design is better than another? In SBPPE decision-making, the decision-maker needs to select an alternative which best meets the demand criteria. Some demand criteria are not as important as others. Some are measured in different scales. Others can be quantitative (e.g., temperature must be 24 °C) or qualitative (e.g., workplace should feel spacious). They can interact with each other (e.g. large windows increase daylighting, but decrease energy efficiency due to heat gain). Performance results for each criteria cannot, therefore, be added up and compared directly. Direct comparison requires a special multi-criteria approach.

Decision methods help people make choices involving multiple-criteria. Decision methods involve calculating overall value using on a "value function" or "decision rule." There are many risks in relying on decision method calculations because of the underlying way each method measures and judges value. Applying of these methods can be difficult, particularly if there are many criteria to process. For many architects, who rely on heuristics and "rules of thumb" to make decisions, using a decision method is a very unnatural way of making decisions. Architects need support, therefore, to use decision methods for processing multi-criteria.

Generally speaking, these barriers to SBPPE relate to the acquisition and application of knowledge, particularly from other (non-architecture) domains. For many aspects the difficulty is not the lack of knowledge, but getting access to it. As I discussed earlier, Post-Occupancy Evaluation in particular, contains a great deal of useful knowledge. Through POE engineers and academic researchers are already aware many of the typical environment problems (and solutions) encountered in workplaces. Why try to resolve a problem each time when someone else has already solved it?

What architects and engineers appear to lack is a collective memory. That is, the ability to draw upon the knowledge of other, more experienced, members of their group when individually faced with a new situation. Within the building industry (and the project team) increasing specialization has led to the isolation of knowledge within domain language and concepts. In this research I propose to break down these barriers by supporting the creation of a collective memory using Information Technology.

II.7. Using IT to Overcome Barriers

In most architectural offices computers support managerial or productive tasks rather than addressing knowledge support. For example, Computer Aided Design [CAD] applications such as AutoCAD are very useful for calculating and drafting, but offer very little for helping architects to remember and apply design knowledge and concepts.

In contrast, engineering phenomena are more easily modelled in terms of mathematics. Dym and Levitt (1991) suggest computers have allowed engineers to assimilate and exploit much more knowledge and at a much faster rate (p. 9). The formalization of engineering knowledge itself into algorithms has enabled engineers to gain a deeper understanding of their domain. As computers have become more powerful, so have they become more capable of processing increasingly complex and sophisticated algorithms to model engineering phenomena such as structural behaviour and fluid dynamics.

During the late 70s and 80s, Knowledge-Based (expert) Systems [KBS] were first introduced as a form of computer-based support for design. For architectural design, KBS systems offer the potential to represent what cannot be captured in terms of numbers or algorithms, the qualitative and heuristic aspects of building design decision-making.

In KBS systems, Artificial Intelligence-based programming allows computers to mimic the same behaviour of human experts while they solve problems. Using this technology, it is possible to escape the idea of the computer as a complex calculator and to think in terms of intelligent assistants that incorporate human expertise. These assistants provide advice and explain problems they are called upon to solve ((Dym & Levitt, 1991) p.10).

Despite some initial success, early KBS design systems were never truly adopted into architectural practice. I believe that this has more to do with the choice of application of KBS technology rather than the technology itself. Many early KBS design systems concentrated on trying to do design rather than support it. This left programmers with the unenviable task of trying to elicit general rules for design, where few rules exist. The ability of KBS to make specialized expertise accessible and available on-demand, however, could still prove to be extremely valuable during certain architectural design tasks. Today, an increasing capacity to integrate KBS systems, Internet, hypermedia, simulation and database technologies offers a richer environment than ever before for the creation of intelligent computer assistants.

To what extent can intelligent tools be used to support SBPPE? In 1996 I undertook a preliminary study to investigate this question (Hill, 1997). Based on the results of that study I concluded that one of the best potential roles for KBS in SBPPE is to support technical decision-making and learning. KBS allows for taking advantage of the mass storage capacity of computers to capture the existing but disperse POE experience of engineers (support for memory). The AI-programming techniques of KBS help architects efficiently search through that memory for lessons-learned to help them make better decisions (support for handling). The KBS programming technique most suitable for providing this type of support is called Case-Based Reasoning [CBR].

The next chapter discusses the issues associated with and applications of Case-based Reasoning in design. It also discusses how I have used this information to create a definition of a CBR system to support strategic design as described in this chapter.

II.8. Summary

In this chapter I have observed that conventional approaches to design office buildings have often failed to produce satisfactory results. This is likely due to the fact that the volume and complexity of knowledge needed to design modern buildings is increasing, making it necessary to disperse the expertise over more than one source. At the same time, in order to avoid an imbalance in the synthesis of a design solution, an architect must exhibit at least a fundamental understanding of the connections between all domains. Within the collective design environment, the separation between these sources needs to be bridged effectively. Despite this, increasing gaps can be acutely felt — particularly in the area of technical issues.

Based on the benefits from risk analysis and total quality management techniques described by authors such as Stuart Brand (1994) and Charles Nelson (1996), it is determined that feedback and consideration of technical issues should occur from the very beginning of the design process. One approach may be to take advantage of the extensive technical knowledge available in existing buildings by finding ways to feed-forward the lessons of Post-Occupancy Evaluation [POE] into the early stages of new design situations.

Strategic Building Performance Planning and Evaluation [SBPPE] presents a theoretical model of early design tasks that incorporates strategic requirement analysis with performance evaluation. The knowledge required to undertake SBPPE in its purest form, as shown in the Building Evaluation Domain Model, is extensive, complex and dispersed over multiple domains. In order to acquire and apply this knowledge effectively architects need additional support.

SBPPE tasks require two main types of support: support for *memory* to efficiently store and recall a wide range of experiences and support for *processing* know how to use information properly. The practical application of SBPPE is uncertain because these types of supports are not commonly available in architectural design environments. In particular, existing sources and tools for technical feedback in early design are missing or inaccurate.

Ideally, the best strategic decision-making support I could offer would be through some form of computer-based decision-aiding and learning support tool that would integrate all relevant cross-disciplinary issues (as described in the Building Evaluation Domain Model). Realizing that architects have a particular problem with the acquisition and application of technical knowledge, however, I believe that environmental engineering of workplaces is an ideal starting point for the development of a multiple-domain (SBPPE) support system.

Although there are various instrumental resources available, I have chosen to concentrate on Case-Based Reasoning [CBR]. In the next chapter, I analyze CBR and explore its relevance for supporting the feeding-forward of technical knowledge into early design phases.

CHAPTER III

Case-Based Reasoning in Design

Principles, Issues & Applications

This chapter introduces Case-Based Reasoning in design. A brief history is provided along with its use, components and development. This includes methods for case representation, retrieval, reuse, revision, and retention. Descriptions of existing Case-Based Design tools are used to illustrate the current application of CBR to design support. The chapter concludes with a proposal for supporting strategic design of workplace environments using CBR concepts and systems.

III.1. What is Case-Based Reasoning?

> *"A case-based reasoner solves new problems by adapting solutions that were used to solve old problems" (Riesbeck & Schank, 1989).*

III.1.1. Knowledge Based Systems

Cased-Based Reasoning [CBR] systems belong to the family of Knowledge-Based Systems [KBS]. KBS are a type of computer program that uses artificial intelligence programming techniques to emulate the behaviour of a human expert as they solve a problem. In conventional procedural programming, the computer is told what to do with data as it is entered, as shown in Figure 3.1. In KBS systems knowledge is separated from control; knowledge is stored in knowledge-base and what to do with it is governed by a separate reasoning or *control strategy* stored in an inference engine (Dym & Levitt, 1991). What distinguishes different types of KBSs is the control strategy used to reason, which in turn, effects how knowledge is represented in the knowledge base.

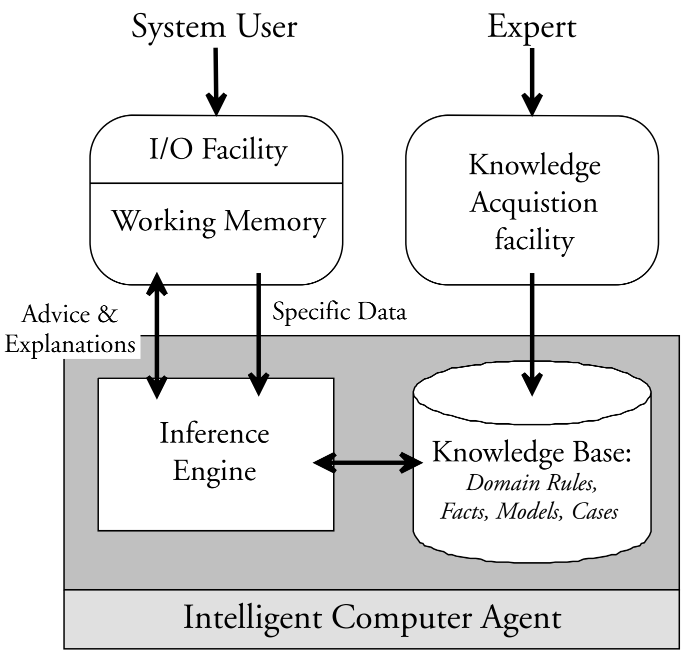


Figure 3.1. Components of a KBS system

III.1.2. Knowledge Representation

The representation of knowledge in symbolic terms is fundamental to knowledge programming. The task is twofold: a representation of the problem (or search) space and a human problem-solver. As a result, the development KBS often overlaps both AI-computer science and cognitive science communities.

Cognitive scientists have determined that humans use many types of reasoning to think about problems including: deductive, inductive, abductive, analogical, classification, common sense, and non-monotonic reasoning. In KBS systems there are four main problem-solving approaches: *Rule-based*, *Constraint-based, Model-based* and *Case-based Reasoning* (Table 3.1.).

Table 3.1. KBS Problem-Solving Paradigms

Paradigm	Description
Rule-Based	Solving new problems by applying rules and strategies used to solve old problems.
Constraint-Based	Ensuring key constraints are satisfied by the proposed solution. Solutions are not "optimal" but "satisfactory."
Model-Based	Solving new problems by applying first principles
Case-Based	Solving new problems by adapting solutions that were used to solve old problems ((Riesbeck et al., 1989) in (Watson, 1997b))

A Rule-based system represents knowledge in the form of facts or (if-then) *rules*. This approach is similar to the human deductive reasoning strategy. Rule-based systems assume there is a generally accepted body of explicit knowledge that most practitioners in the domain can agree upon. This is why rule-based systems have worked well in scientific domains like medicine, where causal effects are often well-known, but not as successfully for creative design tasks where there are no generally agreed upon steps for getting to a solution.

Constraint-based systems ensure key *constraints* are satisfied by the proposed solution. The solutions are not "optimal" but "satisfactory." The use of constraints is similar to an abductive reasoning process where the space of potential solutions is delimited (Coyne, et al., 1989). This approach can be very helpful when there is a well-defined set of conditions that must be met, such as when checking for building code compliance.

Model-based Reasoning [MBR] aims at formulating knowledge in the form of general principles to cover the various aspects of a problem domain

(Davis, 1982). These principles comprise a *model* an expert system may use to solve problems. MBR is sometimes called "reasoning from first principles" (Maher & Pu, 1997). In human reasoning, first principles are derived from an inductive process, where rules, generalizations or predictions are made based on observations about the world. For example, having observed big windows increase the level of daylighting in a room, an expert may predict the need for artificial lighting will be less wherever there are big windows.

Case-based reasoning uses experience or *memories,* represented in the form of *cases*, to solve problems. CBR is related to human analogical reasoning which allows people to recognize something that has not been encountered before by associating it with something that has (Maher, Balachandran, & Zhang, 1995). CBR is quite different from other KBS approaches because it does not require the creation of formal models or rules for how to solve a problem, only a strategy for where to find a solution.

III.1.3. Evolution of CBR

The origin of CBR is attributed to the cognitive scientists Roger Schank and Robert Abelson (1977) who observed that memories and patterns of previous situations (scripts or *cases*) play an important part in both human problem-solving and learning. Evolving out of this research, CBR is a computational model of problem–solving that is based particularly on the memory organization and reminding aspects of analogical reasoning. In terms of CBR in design, researchers are interested in studying how to apply memory organization to define a case memory of previous designs and how to use the process of analogical reasoning to reuse previous design experiences (Maher et al., 1995).

According to Maher et al. (1995) the scope of research CBR in design is defined by two extremes: (1) *autonomous design systems* that independently do design (through adaptation), or (2) *design aiding systems* that support designers with a resource of previous experience.

Before discussing the issues and applications of CBR in design more specifically, the following section first provides a basic introduction of CBR components and concepts.

III.2. The Process of Case-Based Reasoning

> *"Our goal is not to compose rules, knowledge, or cases, but to do what we need to do. Cases/Knowledge just are a by-product of doing stuff. It's getting the information back when we need it that is truly important" (Kolodner, 1996).*

III.2.1. The CBR cycle

A simple example can help explain how a CBR system works. Let us say you are an expert carpenter that has been asked to build a garden shed for a new client. As an experienced builder of garden sheds (with a good memory for such things), you recall other designs you have built in the past that may be appropriate. The sheds you might recall are of the same size, or of the same style required by your new client. After recalling a particular shed design you will consider if it is possible to use it (or some of part of it). To make it work you may alter the design; perhaps make the shed bigger, or allow for changes in circumstances — maybe certain materials used in the original design are no longer available and you need to substitute new ones. After you build the new shed you note how successful the project was and file it away again in your memory, just in case you want to build that shed design again.

Aamondt and Plaza (1994) describes this mental process of CBR as a cyclical model consisting of the *four REs*:

- REtrieve the most similar cases or cases,
- REuse the information and knowledge in the case(s) to propose a solution to the problem,
- REvise the proposed solution if necessary,
- REtain the parts of this experience likely to be useful for future problem-solving.

When a new problem is given to the computer, it is matched against previous cases stored in a case library (or *case-base*) and the most similar cases are *retrieved*. A suggested case is selected for *reuse* and tested for suitability. If the case is not a close match, it may need to be *revised*. The resulting new case can then be *retained* in the case library (Figure 3.2.).

III.2.2. Automating vs. Aiding

In an autonomous, problem-solving *Case-Based Design [CBD]* system, many parts or all of the CBR cycle may occur with little human intervention. For

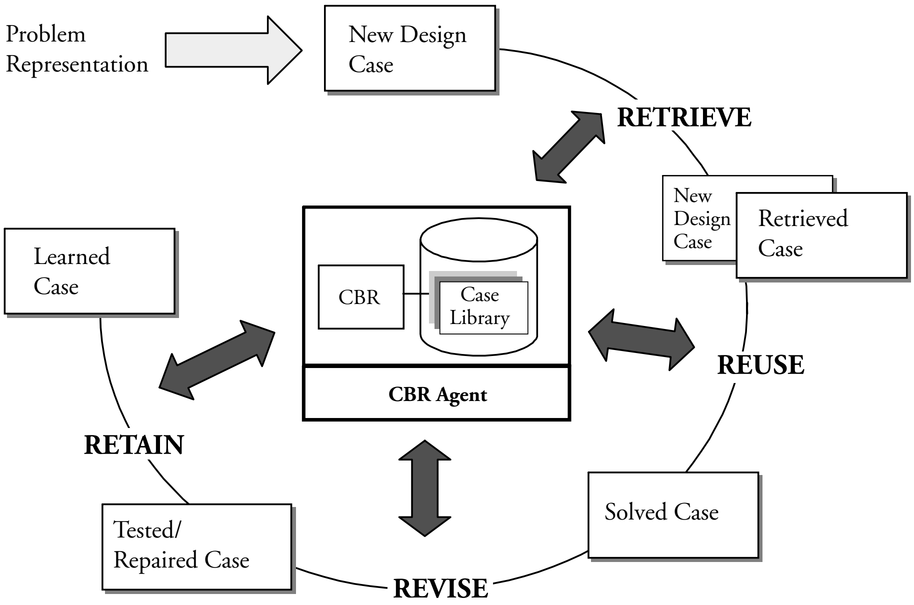


Figure 3.2. Case Based Reasoning Cycle (Aamondt & Plaza, 1994)

example, for the garden shed design example above, the system would recall sheds, decide what changes to make, and modify and evaluate until it came up with a solution to fit the new situation.

In supportive, or *Case-Based Design Aids [CBDAs]*, the CBR process involves human interaction. Many CBDAs are used only to retrieve cases for reuse, and leave case revision (i.e. adaptation) up to the system user (i.e. the designer).

Types of support. CBDAs generally offer two forms of support: *interpretive* and *stimulative*. Interpretive systems concentrate on identifying previous cases for comparison (how similar is this to the last time?) and contrast (how is this time different?). For example, in the garden shed example, let us say you want to build a new shed with a specific floor area. To fit a retrieved case to the new situation requires determining what changes and what can stay the same. For example, a 4 m^2 square shed can be made into a 9 m^2 square shed if you know to change the length of the walls from two metres to three metres, but keep the wall heights the same.

Stimulative CBDA systems use cases for decision-aiding and teaching. According to Dutta, Wierenga and Dalebout (1997), stimulative CBR systems promote creative decision-making by story-telling and enhance learning by advising about the decision situation (see Figure 3.3.). To explain stimulative support, let us return to our garden shed example. This

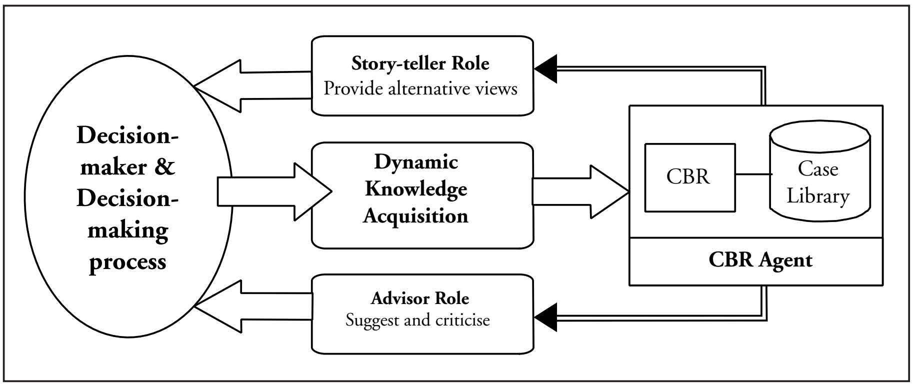


Figure 3.3. Stimulative CBR (Dutta, Wierenga, & Dalebout, 1997)

time however, instead of building a garden shed yourself, you want to teach someone else how to build one.

The best way to learn how to build a garden shed is to build one. To become as good at shed-building as you, the experienced carpenter, your student will need to build a lot of sheds. Building a lot of sheds time-consuming and expensive way to learn, but you can help your student by giving them a similar learn-by-doing experience. You can tell them stories of how you learned — such as that time you used ungalvanized nails and they rusted, or when you decided to use clay instead of asphalt roof tiles and the shed collapsed under their weight. In this way, you give your student your experiences so they can make better decisions in the future (at least about nails and roof tiles).

So far, how CBR cycle in design works at a conceptual level has been described. The actual computational implementation of CBR raises a number of issues that generally fall under one of two categories: *representation* and *control*. Representation issues relate to the problem of trying to capture and store knowledge in the form of cases in the computer. For example, what is in a case? Control issues relate to the problem of teaching the computer to use cases to reason. For example, when and how will a case be retrieved?

The next sections summarize some key implementation issues and highlight the main computational techniques used to create CBR systems in the past. More detailed descriptions of CBR systems are given in (Aamondt et al., 1994) (Kolodner, 1993), (Leake, 1996) (Watson, 1997a; Watson, 1997b) and (Bergmann, Breen, Goker, Manago, & Wess, 1999). A comprehensive book relating specifically to CBR in design is *Case-Based Reasoning in Design* by (Maher et al., 1995).

III.2.3. The Case-base

The set of cases stored in a case-base is the primary source of knowledge of a CBR system. The most basic requirement of CBR is the formalization of pieces of knowledge, each piece representing an *experience*, into the form of *cases*.

The development of a case-base involves: (1) defining what is the content of a case, (2) how to represent case content, and (3) how to organize the cases in the case base.

III.2.3.1. Case Content — What is a Design Case?

> *"A case is a conceptualized piece of knowledge representing an experience that teaches a lesson fundamental to the goals of the reasoner" (Kolodner & Leake, 1996) p 36.*

The content of a case in a CBR system can be many things:

- a story or lesson to be learned (Kolodner, 1993)
- an account of an event (Watson, 1997b), or
- the process by which a problem is solved (Flemming, Coyne, & Snyder, 1994).

A case is a piece of knowledge that is going to help someone solve a problem in the future. The lesson a case teaches should be relevant to the goals of the reasoner. Perhaps it is a new way of achieving a goal, explains a goal reached with a great deal of effort, outlines when there were unexpected results in trying to achieve a particular goal, or when new goals arose.

Case content is typically subdivided into a *problem* description and the derived *solution* to that problem. The problem describes the situation in which the experience occurred. The solution part contains the reusable part of the experience. For example, in medical diagnosis, the problem part is a set of observed symptoms and the solution part is the description of the diagnosis and possible remedy. During retrieval, the problem part of the case is used to find stored solutions. A new problem is compared with problem descriptions in the case-base and the case with most similar problem description is recalled along with its stored solution (Figure 3.4.).

Most experiences designers have in doing design (design problem-solving episodes) are too complex to be represented by a single case. This is why most CBR design system developers tend to "chunk" or break cases up into smaller subcases. Other researchers, to accommodate the multi-dimensional ways in which designers view design problems, extend the

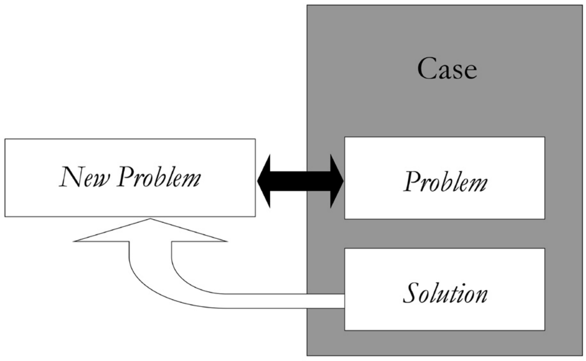


Figure 3.4. Basic view of Case Content

concept of problem and solution descriptions further by differentiating case information according to function, behaviour, or structure [FBS]. (See also "Integrating Model-based Representations" later in this section.)

Design cases found in existing applications of CBR in design come in all shapes and sizes. Some examples are listed in Table 3.2..

Table 3.2. Types of Design Cases

Case Content	**Name of System**
Problem, Solution, Creation Method	SEED
FBS Models	Kritik, FAMING, CASECAD, CADET
Plan actions, Physical Components, Specifications	PANDA
Images, Gestalts, Value Tuples	FABEL
Multi-media (i.e. text, CAD drawings, photographs),	CADRE, CASECAD, ARCHIE

From: (Maher et al., 1997)

III.2.3.2. Case Representation Techniques

> *"It is the structure of the data representation that enables us to draw meaning or information from data" (Watson, 1997a) p. 14.*

There are various methods for formally representing cases in the computer. Cases are conventionally represented as "flat" records of *attribute:value* pairs, as in databases. This is useful when experience can be easily described by a list of features.

In domains, like design, where experiences have structured relationships (i.e. have complex sub-parts or additional knowledge is needed besides the cases to satisfy goals) a more sophisticated approach to representation is required. In a *structural CBR approach* attributes and values are pre-defined according to a *domain model.* (Bergmann et al., 1999). The structure of the domain model is then captured in the computer using relational or object-oriented data representation.

In relational databases, each case has its own unique identifying codes called *keys* and case descriptions are distributed over multiple tables. For example, in a sales support system for pre-fabricated garden sheds I can determine the colour of Garden Shed A is "green" through a colour-relational table (Figure 3.5.). This means for a shared attribute like "colour" a data item like "green" only needs to be stored once.

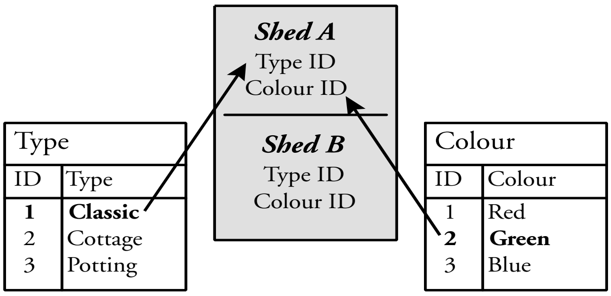


Figure 3.5. Relational Representation

In object-oriented representations individual records are stored as *instances* of *classes*. For example, in an object-based system, "Garden Shed A" and "Garden Shed B" would both be instances of the object-class "Garden Shed." As illustrated in Figure 3.6, the object-class "Garden Shed" defines all attributes that are common to sheds such as: structure, manufacturer, and price. "Garden Shed A" as an instance of "Garden Shed," automatically *inherits* all of the characteristics of that class.

The significance of these advanced computer representation methods is they allow us to capture the structure of a domain model. The structure, not the data, contains the real knowledge from the domain. In other words, we may know lots of facts about a subject, but it is the expert that can tell us how the pieces all fit together and relate to each other.

Not all parts of a case are always formally represented. According to Bergmann et al. (1999), the degree of formal representation of the solution part of a case depends on the degree of automatic support for re-use. For example, CBD systems such as SEED that place more of the burden of design on the computer (i.e., to do or support adaptation), require cases to

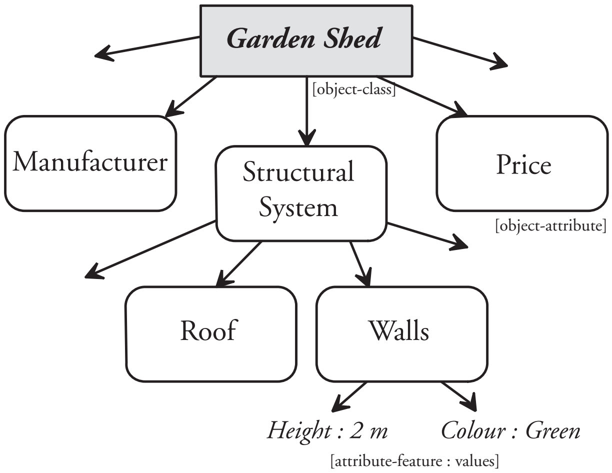


Figure 3.6. Object-Based Representation

include much more explicit representation of parametric or causal knowledge (Domeshek, Kolodner, & Zimring, 1994). In other words, there is a need to store the steps and constraints used to create a design as part of the solution description to use them again. CBDA systems that leave the re-use of cases up to the system user do not require the solution part of the case to be formalized at all. In fact, it is better if they do not. For highly interactive retrieval systems, informal case representations understandable to human designers (such as textual descriptions and graphical illustrations) make browsing much easier. For example, ARCHIE, CADRE and CASECAD use various types of hypermedia to represent design solutions.

III. 2.3.3. Case Organization

So far, the discussion has focussed on the content and representation of individual cases. How cases are organized in relationship to each other is also important to consider, as this can make searching through and retrieving cases much more efficient.

At a conceptual level, *memory organization* refers to an internal representation of how people remember things (or are reminded of something). Cognitive scientists theorize that we structure our general knowledge about situations around *scripts* or descriptions of stereotypical events such as going to the grocery store, or dropping off dry-cleaning.

If we lack experience with doing something, we recall the specific instance where we encountered it before. For example, a grocery store with a unique feature like an automatic bottle depository. However, if we have experienced something a lot, we tend forget the details (e.g., the name of all the stores), but remember the patterns associated with the experience. These patterns are what Roger Schank (1982) refers to as "memory organization patterns" or MOPs. For example, when we go to a new store and want to pay, our ability to recall the pattern of all previous experience of stores lets us know that somewhere near the exit there will be a cash register.

The organization of cases in a case-base is intended to make searching through the cases easier and more accurate. Maher, Balachandran & Zang (1995) refer to three types of structures used in design case-base memory organization: *flat structure*, *feature-based structure*, and *hierarchical structure*.

In flat structures, cases are stored individually and retrieved by name. For example, "Store A", "Store B" and so on. This type of structure is quite simple and it is easy to update, but requires all cases must be searched each time which is inefficient and costly in large case-bases.

In feature-based structures, key features of the cases are identified and stored separately with pointers to the cases that have these features. Cases are then retrieved based on the similarity of their features with features of new problems. For example, a search for "store" and "automatic bottle depository" would retrieve "Store A" (see Figure 3.7.).

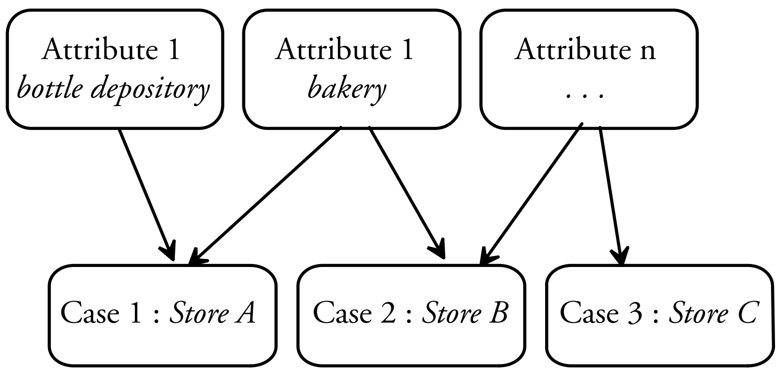


Figure 3.7. Feature-based Structure

In hierarchical structures, key features are used to differentiate between cases, but they are also placed in order of importance according to a domain model. In hierarchical structures cases are categorized by shared features, and then further differentiated from each other with more specific features. During retrieval, moving through the structure has the effect of progressively limiting searches within case memory to a subset of cases that match on the most important key features first. For example, a store with a bakery may be clustered under with a subset of cases "building-type: grocery-store", "size:large", "feature:bakery" (see Figure 3.8.).

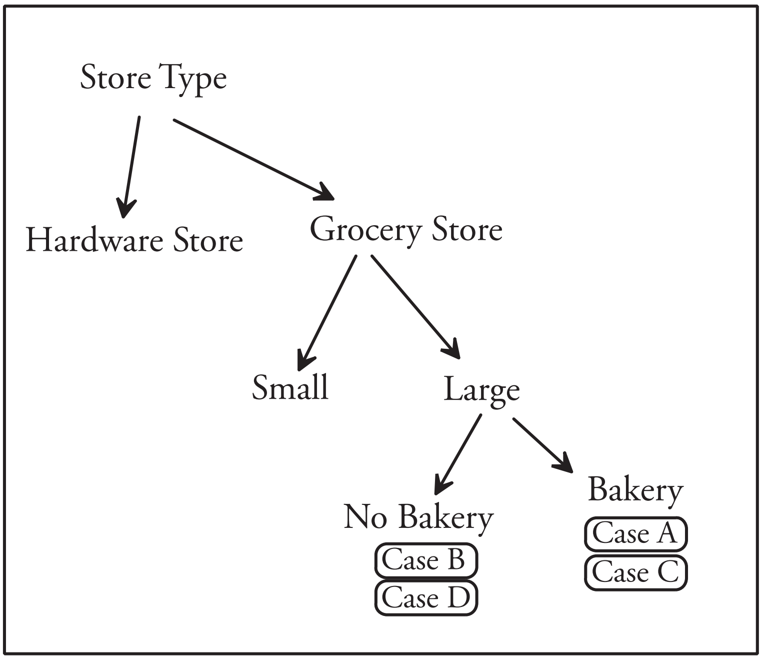


Figure 3.8. Hierarchical Structure

Although using a hierarchical structure can increase the efficiency of searching, it does introduce a bias in the search. There is a risk of overlooking a potentially useful case if the features used to eliminate "irrelevant" sets if cases are ordered incorrectly. In our example structure above, it is impossible to retrieve small grocery stores with bakeries. Since the importance of features changes depending on the problem to be solved, the organization of the structure needs to be considered carefully, taking into consideration designers may need to access both specific case content as well as more general domain knowledge.

The use of storage methods (such as those described above) that reflect the conceptual view of the information being stored is intended to support efficient search and retrieval. Such methods overlay an additional level of complexity over case storage and require good domain analysis. It should be noted there are several more sophisticated well-known memory organization, or *case memory modelling* methods described in domain literature such as *dynamic-memory* (Schank, 1982) (Kolodner, 1983) and *category-exemplar* (Porter & Bareiss, 1986). To date, however, these methods are not used in commercially available (non-academic) CBR systems. Watson (1997a) states in "real" systems, programmers have found it adequate to either store cases as simple flat file data structures, or within conventional relational database structures and use indexes to reference cases.

III.2.3.4. Integrating Model-based and CBR representations

In addition to representing specific knowledge about a design case it is also possible to integrate more abstract or general design information into case memory using *design models*. According to Maher, Balachandran & Zang (1995), while individual cases represent individual instances, a *design model* contains general knowledge about different kinds of design cases.

Of the various design models implemented in CBR systems described in the literature, the most commonly used (and most relevant to this research) is the FBS model. In this representation *attribute:value* pairs are used, but are grouped into categories of either:

- Function (What is the design for? What does it do?)
- Behaviour (How does the product behave under the specified conditions?), and
- Structure (What is the artefact made of?).

A hierarchical structure developed out of a FBS model (where cases are represented under more general categories) can be implemented in a computer in an object-oriented representation. Design *classes* represent design models and design *instances* represent cases (Figure 3.9.).

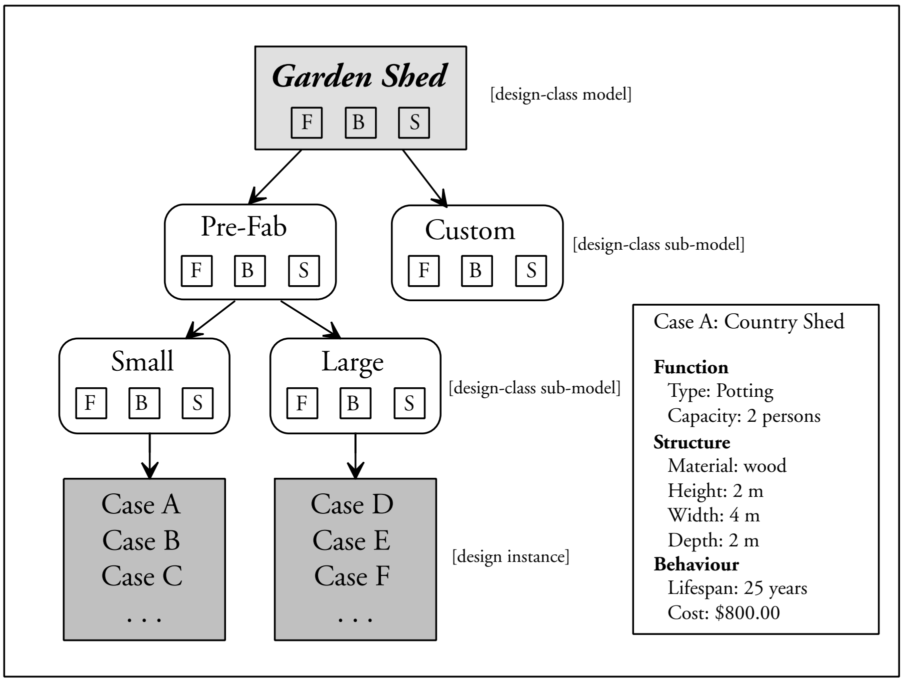


Figure 3.9. Fictional Design Case Representation with FBS Modelling

Later, Chapter V describes how the need for strategic designers to have more than just a physical description eventually led me to adopt a similar method for representing both general and case-specific design knowledge. For the purposes of implementation, a relational representation is used.

This section has described how design cases can be represented and how to organize cases in a case-base to support the efficient retrieval, but how does retrieval in CBR systems actually happen? The next section talks about this process.

III.2.4. Retrieval

> *"Psychologists have found that people are comfortable using cases to make decisions (Ross Klein;Read) but don't always remember the right ones (Holyoak;Gentner). To alleviate this problem the computer can be used as a retrieval tool to augment people's memories" (Kolodner et al., 1996) p. 61.*

Databases are probably one of the most common ways that people use computers to store and recall information. Database systems and CBR differ subtly in how they retrieve and store data. With database retrieval you have to know exactly what you are looking for. Database retrieval uses a language, such as SQL, to retrieve an item or set of items that *exactly* matches the query the user enters. Because of this, database systems can easily be prevented from returning an answer because of queries worded differently or containing simple spelling mistakes.

In CBR you can retrieve cases that are not necessarily identical, but have a *close* match, however "close" is defined. This provides the user with much more flexibility, given that most problems people encounter do not present themselves exactly in the same way as ones they have encountered before. CBR will also allow you to modify the query several times while using it – allowing you to refine your search for a "good" or "better" match. CBR can also help you in the definition of your problem, by taking you through cycles of refinement.

During retrieval, a CBR system uses an algorithm to search for a match between a new problem (the question or *target case*) and one of the problem-solution descriptions (the answer or *source case*) it has in its case-base. Retrieval assumes the source case with a problem description that is most similar to the new problem will also contain the (near-) best solution. The retrieval algorithm relies heavily on the indexes and the structure of case memory to direct the search to appropriate cases (Watson, 1997a).

The subtasks of retrieval are:

1) indexing,
2) retrieving cases (similarity and ranking), and
3) selecting and recalling cases.

III.2.4.1. Indexing

Indexes are used to make retrieval more efficient. The issue of indexing is not important for small case-bases, but becomes critical for large ones. Index information is a set of key information or labels stored for each of the cases and held in memory. As a result, you do not have to search the whole case-base, only the index. For example, if "age" is an indexed feature, you could say, "show me only cases where people are between the ages of 35-40."

An index is drawn from the case descriptions. According to Griffith and Domeshek (1996), indexing involves "exploring the possible descriptions of objects, concepts, and relationships in the domain" (p. 70). Most importantly the purpose of indexing is to make cases and other knowledge accessible at when it is needed in the future. So, above all, indexes need to be *predictive*.

How do developers select which design features to use in an index? Indexes should meet several criteria:

- Prediction — captures linkages between previous situations and new (i.e. aspects of design critical to determining design solutions.),
- Extent — covers all intended uses,
- Specificity — provides a level of detail needed to differentiate between cases,
- Generality — provides a level of abstraction to allow for inexact and near/similar matches, and
- Usability — corresponds to domain language and mental model of task and domain; (e.g., reflects how other designers will refer to designs; see also III.2.4.2. *Indexing Vocabulary*).

A good example of indexing of a CBDA is ARCHIE-2 (Griffith & Domeshek, 1996). ARCHIE contains building design stories as cases. ARCHIE-2's indexing scheme contains the following:

- issue it addresses
- what a thing is (physical description)
- what it does (functional subsystem/purpose)

- stakeholder it pertains to, and
- lifecycle stage it is about.

III.2.4.2. Indexing vocabulary

An indexing vocabulary is a subset of the vocabulary used to describe entire cases. It identifies a set of features used to label cases. According to Leake (1996), the best indexing vocabulary is drawn from the concepts that naturally come up in the course of carrying out reasoning tasks. Sometimes, however, the vocabulary used to create the case differs from that of the person re-using the case. This is why Kolodner et al. (1996) remark, "while indexes are chosen for particular cases, an indexing vocabulary needs to cover the domain or set of domains to be handled by the system" (p. 44).

Establishing an appropriate indexing vocabulary for the domain of building design is especially challenging. Building design is multi-disciplinary, with each discipline having its own terminology. Some may argue most architects do not use a textual vocabulary at all, but rely instead on graphics to talk about and recall designs. Building design is also evolutionary; with design problems initially ill-defined becoming defined through the design process itself. From an indexing and retrieval point of view this can mean using *situational assessment* to enable the computer to select the appropriate index to use and allowing for problem (target case) descriptions to change or be refined over time (e.g., based on browsing and retrieval of initial cases with incomplete or abstract problem descriptions).

III.2.4.3. Retrieving Cases

The role of the retrieval algorithm is to retrieve and rank the best matching cases to the current problem. A variety of algorithms are discussed in domain literature. According to Watson (1997a), the two techniques for retrieval most commonly used by commercial CBR tools are: *nearest-neighbour* retrieval and *inductive retrieval*.

Nearest neighbour retrieval involves the use of an algorithm that calculates the relative distance of a new case (the *target case*) to the other cases in the case base (*source cases*). It does this using the values of indexed attributes. The smallest distance value gives the "nearest neighbour," the case sharing the most similar attributes. Attributes in the formula can also be *weighted*. This means the nearest neighbour is selected based on how similar certain key attributes are between the target and source cases.

Inductive retrieval originates from the domain of machine learning. It relies on the analysis of case data in the system to dynamically generate rules or a decision tree that organizes (or indexes) the retrieval of the cases. The computer (automatically) or a human programmer (manually) figures out ahead of time what features are important to search on and, in what order.

Nearest neighbour retrieval is potentially slower and less efficient than inductive retrieval. This is because the features of the target case have to be compared with the features of all of the source cases in the case base (a calculation per feature per case). Cases indexed on lots of features, or a very large case base, can take a long time to process. Inductive index trees make retrieval quicker, but developing and maintaining the index itself can be time-consuming. I discuss my decision to use a form of nearest neighbour retrieval using multi-attribute similarity matching in Chapter VI.

III.2.4.4. Selecting Cases

As described earlier, a CBR system selects cases from its case library based on their similarity with the target problem provided by the system user. Selected cases are ranked based on the results of the similarity measures. Sometimes a two-step procedure is used in which another more detailed similarity measure is applied after the first selection to further distinguish between cases. Once a case is selected from the list its solution is retrieved for re-use.

III.2.5. Re-use and Revision

The basic goal of a problem-solving CBR system is to find a solution for a problem using cases in its case library. It can do this in several ways: (1) giving you a list of cases most *similar* to your problem, (2) trying to *re-use* one of its cases as the solution, or (3) *adapt* one of its cases (or parts of multiple cases) to better fit what you need. (Watson, 1997a).

During retrieval, if the source case problem matches the target problem, the source case solution is assumed to satisfy the target problem. The retrieved case then simply can be reused. When the source case only partially matches or its solution is incomplete, however, the case needs to be adapted.

The first step of adaptation is deciding what to keep and what to change. After that, modification can take place in several ways. The recipe design program JULIA, Janet Kolodner (1993) uses several methods of case adaptation (Table 3.3.).

Adaptation is the most difficult part of a CBR system to implement. It is for this reason it is usually avoided. Several systems assist or semi-automate the

Table 3.3. Methods for Adapting Recipe Cases in JULIA.

Method		Example
Substitution	Reinstantiation	Replace chicken for beef in recipe
	Parameter adjustment	Increase amount of ingredients in recipe
	Local search	Look for "oranges" instead of "lemons"
	Query memory	Look for "vegetarian"
	Specialized search	Look for something "like beef"
	Case-based substitution	Look for "Italian meal" to replace "lasagna"
Transformation	Common sense	Replace, delete, add "item" (e.g., beef)
	Model-guided repair	An Italian recipe consists of x, y, z
Special purpose		Add instructions for clarifying butter to recipes with butter
Derivational replay		Use same *method* used to create previous recipe

From: (Kolodner, 1993)

design synthesis process using techniques such as (1) formulating constraint-satisfaction problems [CSP] as in JULIA and CADSYN, (2) integrate rules or model-based reasoning [MBR] as in KRITIK, or (3) provide specialized adaptation environments that offer a variety tools for topological and dimensional adaptation and case combination, as in FABEL and CADRE. In other systems, adaptation is left entirely to the human designer, as in ARCHIE. (See also Table 3.4. - Case-Based Systems in Design)

Not all CBR design systems need to provide designers with design solutions. Cases can also be used for prediction, comparison and contrast, and education in design. Justification and interpretation of design problems can be a particularly significant role for CBR in supporting early design where design problems tend to be ill-defined, open-ended or fuzzy-bordered. At the beginning of the design process most architects are seeking an understanding of the problem rather than a particular solution. An important role for CBR in design, therefore, could be to provide support for learning about the problem itself. Assuming the world is a consistent place, in which things learned in the past will be useful in the future, CBR systems should be able to use cases for comparison (how similar is this to the last time this situation occurred?) contrast (how is this time different?) and lessons (unexpected problems and successes) to improve design decision-making.

III.2.6. Retaining and Learning

> *"The benefits of a CBR application stand or fall on the content's topicality" (Bergmann et al., 1999).*

The ability to learn from experience is what Kolodner and Leake (1996) describe as one of the hallmarks of a case-based reasoner. For example, the more garden sheds you build, the better you are likely to get at it and the less mistakes you will make each time. It also helps if your experience is up-to-date; that the last shed you built was less than fifty years ago.

Like any novice, most CBR systems are likely to begin with an incomplete or incorrect knowledge base. According to Kolodner and Leake (1996) *seed cases* should cover:

- the range of reasoning tasks the system will be responsible for doing or supporting (goals and tasks), and
- the range of well-known solutions for these reasoning tasks.

Once a CBR system is in-use the case-base can be built up incrementally by finding out what is missing through trying to use the existing cases. Maintaining a case-base properly means adding new cases, updating the domain model (indices, memory structure…etc.), editing old cases, eliminating unused or incorrect cases, and keeping track of situations where the existing case-base was unable to help. To achieve all this means having a plan and a means for maintenance.

The importance of the retaining and learning stage of the CBR cycle cannot be overemphasized. Small case-bases can be useful, but they do need to cover the topic adequately and they need to be up-to-date. It is important that knowledge in the system, represented in the case data and the domain model, is updated on a regular basis. Companies using CBR systems usually employ a database systems administrator or a *case-builder* to be responsible for reviewing cases, monitoring case-base use, and maintaining the case-base.

Within CBR literature there are several references to research that concentrates on developing CBR systems capable of enriching their own knowledge-base over time. This means using learning processes to automatically capture new cases to help solve or interpret new problems — for example, by combining CBR with data-mining or induction techniques or through active connection to the "real world" with monitors or sensors. In SEED, the various design problem specifications and solutions the users create while using the system are automatically captured and stored in the database of the system.

In the commercial application of CBR the most successful examples are Help-Desks. Help-desk applications are used and filled by a *group* of people rather than an individual, which make them an excellent example of the advantages of storing, sharing and reusing collective experience. The fact that help-desk CBR systems are maintained and updated by the end-users is key. Enabling end-users (not the operators, but the organization's database system administrators) to update the case-base with easy-to-use case authoring tools or decision-tree editors avoids expensive and time-consuming knowledge engineering. Allowing end-users to maintain the case-base is undoubtedly the best way to keep a case-base from becoming out-dated and it provides a strong argument against using overly complex representation structures and retrieval methods common in many academic applications.

III.3. Applications of CBR Systems in Design

> *"What is required here is an understanding of the processes used by our users: how do architects think about their task during the early stages of design" (Griffith et al., 1996).*

III.3.1. Using CBR Systems

III.3.1.1. What are CBR systems good for?

Current CBR applications are generally used for two main problem types:

1) classification tasks — determining what type or class a new case is and relating it to existing cases, and
2) synthesis tasks — creating a new solution by combining parts of previous solutions.

Most commercially available CBR tools support *classification tasks* (e.g., diagnosis, prediction, assessment, process control, and planning). A typical example is a helpdesk application where the user tells the CBR system the problem he or she is having and it finds the solution that fixed the problem in the past.

CBR tools that support *synthesis tasks*, such as design, must use adaptation. They are usually hybrid systems that combine CBR with other techniques. Tasks involving synthesis are very hard to implement, so generally the creative process is simplified — using the known-to-be-good-before design(s) from which a final design can be produced through simple adaptation. The assumption is, any solution is better than starting from scratch, but is this really the part of the design task computers should be doing?

Design, especially strategic design, is an iterative process in which a great deal of complexity and creativity exists in creating, evaluating and refining design alternatives. The current application of CBR techniques to synthesize solutions for design problems is extremely limited by the availability of appropriate cases and lack of standardizable (creative) adaptation routines that can handle the complexity of evaluating solutions and effecting repairs. In short, humans can synthesize better than CBR systems. CBR systems, however, are much better than humans in classification tasks, such as being able to remember and recall cases to aid in the formulation of design requirements or to support the comparison and contrast of design concepts. Classification problems are easier to solve using CBR because they fit the characteristics of CBR better than synthesis problems (Watson, 1997a).

III.3.1.2. When should you use CBR systems?

Watson (1997a), says to use CBR systems when you have a poorly understood problem area with complex data that changes slowly with time and justification is required. CBR systems should not be used when case data is not available, or if complex adaptation is required, or if an exact or optimum answer is required.

A problem with other KBS approaches is computers need to be taught how to infer solutions from facts using rules. Determining rules for "how to design" is very difficult since it is hard to describe in a precise set of linear steps and rules what designers do when they design. On the other hand, a lot of architectural case data is available, imbedded in the form of existing buildings. Fitting an existing building design case for use in a new situation is poor role for CBR systems because it requires creativity and the ability to do complex adaptations. Providing a means of representing and then classifying existing building design cases according to their similarity to new design scenarios, however, is something CBR systems could do well. Once an architect completes a project, or if they were never part of it to begin with, it can be very difficult to retrieve design information. As a knowledge-management tool for POE information, CBR could potentially help stop architects from re-learning lessons, particularly ones someone else has already learned the hard way. The best use of CBR in design is, therefore, not *solution* transfer, but *knowledge* transfer.

III.3.1.3. What makes a CBR system's reasoning successful?

The usefulness of CBR applications is they take advantage of what is already known, without having to waste time deducing solutions all over again from rules and first principles. For complex problems like designing buildings, starting with something is much easier than starting from scratch. According to Kolodner and Leake (1996) the quality of a CBR system's reasoning is based on five things:

1) The experience it has had or been given,
2) Its ability to understand the relevance of old experiences to new situations,
3) Its adeptness at adapting prior solutions to fit new situations,
4) Its adeptness at evaluation of new solutions and repair of flawed solutions, and
5) Its ability to integrate new experiences into its memory appropriately.

The experience a CBR system is contained in its case-base, which need not be large, but should cover the majority of the problem space and be up-to-date. A CBR system's ability to understand the relevance of the cases in its case-base to new situations depends on the quality of the similarity measure it employs. The re-use and adaptation of cases requires additional algorithms capable of maintaining constraints and critically evaluating evolving solutions. CBR applications that concentrate only on retrieval, however, do not need to be adept at adaptation, evaluation or the repair of new solutions. A natural consequence of using a CBR system to solve a problem is it generates a new case, but solutions created outside of its environment need to be added by end-users. It is important for the continued usefulness of a CBR system to be able to easily acquire and integrate new cases, so a non-generative CBR system needs a good facility for adding cases.

III.3.2. Case-Based Systems in Design

The main applications of Case-Based Reasoning in design are to support:

- Maintaining a memory of previous designs,
- Generating design solutions, and
- Learning about design

Table 3.4. contains a listing by task of applications of CBR to design. All but one of the systems (CLAVIAR) are non-commercial, "academic demonstrators." This list is representative, but it is certainly not complete. It is intended to represent the variety of design tasks to which CBR has been applied.

Table 3.5. Case-Based Systems in Design

	Name	What it does	Reference
Design Education	Architectural Case Library	Interactive case-base of building designs	(Heylighen, Segers, and Neukermans 1998)
	EDAT	Case-base of landmark designs	(Akin et al. 1997, 6:265-274)
	SAM	On-line case-base of structural designs	University of Sydney (Maher and Simoff 1998)
CB Design Systems	CADSYN	Structural design of buildings	University of Sydney (Maher and Zhang 1991)
	FABEL	Component-based building design	(Voss, 1997)
	SEED	Conceptual design of buildings	(Flemming et al., 1994)
	CADRE	Building design layout	EPFL/ETH Zurich (Hua, 1994) (Faltings, 1997a)
CB Design Aiding Systems	EADOCS	Composite sandwich panels	Delft U. of Tech. (Netten, 1997)
	BRUSH	Bathroom redesign for disabled people	University of Sydney (Bridge, 1997)
	IDIOM	Spatial layout of buildings	EPFL/ETCH Zurich (Lottaz, Stalker, & Smith, 1998; Smith, Stalker, & Lottaz, 1996)
	CASTLES	Retaining wall selection	(Yau & Yang, 1998)
	BDA	Building systems analysis	(Papamichael, LaPorta, and Chauvet 1997, 6:341-352)
	ARCHIE(II)	Conceptual design of office buildings and courthouses (ARCHIE I)	(Domeshek & Kolodner, 1992)
	CASECAD	Structural design of buildings	University of Sydney (Maher, 1997)
	NIRMANI	Briefing of warehouse buildings	(Perera & Watson, 1995)
	RODEO	Reuse of design objects in CAD	University of Kaiserslautern (Altmeyer, Ohnsorge, & Schürmann, 1994)
Non-Architectural Design	AIDA	Design of Aircraft	Delft U of Tech. (Rentema, Jansen, & Torenbeek, 1998)
	NESTEC	Roasting and Decaffeinating Coffee	EPFL (Faltings, 1997b)
	FAMING	Mechanical devices (autonom.)	EPFL (Faltings & Sun, 1996)
	MIDAS	Conceptual design of aircraft subsystems	(Domeshek, Herndon, Bennett, & Kolodner, 1994)
	KRITIK(II)	Conceptual design of physical devices, e.g heat exchangers	(Goel & Chandrasekaran, 1992)
	CLAVIER*	Parts layout for autoclave	(Hennessy, and Hinkle 1992)
	ASKJEF	Multi-media design support	(Barber et al., 1992)
	CADET	Mechanical devices	(Sycara et al. 1991, 4:157-188)
	JULIA	Meal planning	(Hinrichs, 1988)
	CYCLOPS	Landscape design (evaluation)	(Navinchandra, 1988)1988

III.3.3. Issues relating to Application of CBR in Design

The technology required to create a CBR system a small issue when compared to the potential impact using it is likely to have on designs and designers. According to Schmitt, Dave and Shih (1997) some general issues arising in the current application of CBR to architectural design are:

1) the representation of design and design cases
2) relation between CBR and design creativity
3) legal aspects, and
4) integration with other CAD systems.

The pros and cons of CBR in design summarized in Table 3.5. and discussed on the next pages.

Table 3.4. Pros and Cons of Case-Based Design

Issue	Pros & Cons
Representation of Design & Design Cases	PRO – Ease of use. Formal representation of design is not required.
	CON – Case collection and indexing.
CBR & Creativity	PRO – Consistent recall and access to a broad range of (critiqued) cases.
	CON – one-to one mapping and synthesis of design solutions.
Legal Aspects	PRO – maintenance of corporate memory.
	CON – intellectual property, plagiarism.
Integration with other Systems	PRO – new cases generated naturally out of the process.
	CON – use of special CBR design tools and environment, rather than popular commercial systems.

Intuitive Approach. For design, the key part of the activity lies in how a designer reasons about what they know (Coyne et al., 1989). Reasoning is how a designer creates something new with their expertise. The CBR process model is similar to the task model for the architectural conceptual design process. According to Dave, Schmitt, Faltings and Smith (1994), the practice of using precedent cases starts in early architectural education and continues on into professional practice. Many architects should therefore find CBR systems easier to understand and use than other forms of KBS support based on the similarity to their own training and intuitive way of reasoning.

Case Representation. In building design, the path leading to the solution is usually not well-documented, but the physical solutions usually are. Though potentially costly if not done as part of the design process, the performance of any existing building can be captured through POE. A critical advantage of CBR over most KBS system approaches is design knowledge does not need to be represented explicitly as rules or constraints. Often both the source and target case can be described in "natural language." Although capturing knowledge in disciplines lacking strong domain theory is easier with cases, care still needs to be taken to determine what and how case information is indexed and stored in order to make it useful for solving new problems.

CBR and creativity. Creative design is often an intuitive process of determining multiple solutions, redefining, elaborating and manipulating the original problem boundaries. The creative design process is highly memory-intensive and relies on past design history, which provides a strong argument for the use of CBR systems (Wills & Kolodner, 1996). CBR tools are capable of doing something human designers are unable to do as quickly and consistently — recall past design histories that might inform or inspire the creative process.

As mentioned earlier, CBDAs are decision-*aiding* systems. They:

> "...help designers by making available to them a broad range of critiqued designs that can serve to highlight important design issues, to explicate abstract design guidelines, and to provide suggestions or warnings about possible design solutions" (Griffith et al., 1996) p. 66.

Autonomous CBD systems go a step further and actually seek to *generate* new design solutions.

Two key assumptions about design retrieval and solution generation in CBR are:

1) the specification of the new problem can be mapped directly onto an appropriate solution stored in case memory, and
2) cases recalled by the system can immediately satisfy, perhaps with some adaptation, the design problem described by the designer.

One-to-one mapping assumes the specifications for a new design problem are well-defined and the retrieved case will fit the problem specifications, perhaps with some adaptation (Figure 3.10.).

Design specifications are often ill-defined, incomplete and are likely to change and expand as the design process continues. To address such ill-defined problems CBD system developers sometimes incorporate tools for situation assessment. This is a process which precedes search and is used

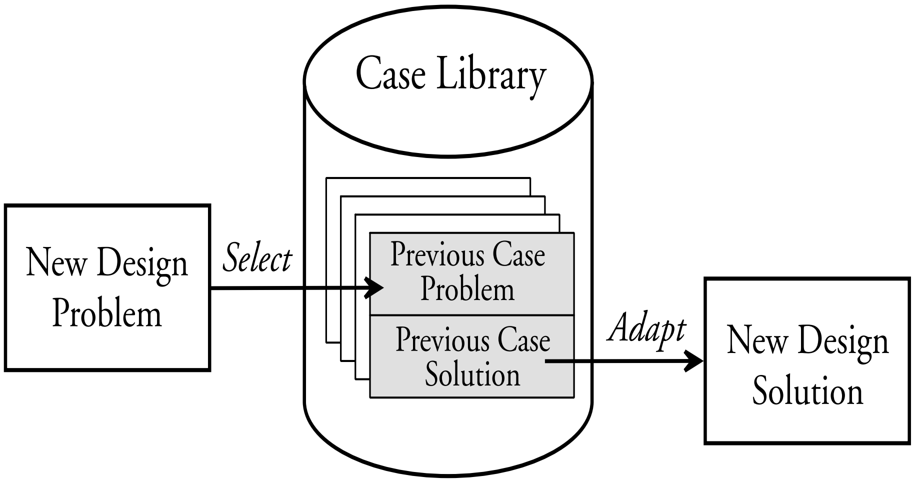


Figure 3.10. One-to-One Mapping

to "interpret a new case or query and elaborate its representation to bring its description more in line with what might be stored in the case library, thereby enabling relevant cases to be recognized even if they are represented differently" (Kolodner, 1996). Other developers use methods that allow for multiple searches or index revision.

Design generation. Generally speaking, cases in a case-based design support system provide a starting point for the generation of new designs solutions (Maher et al., 1995). In conventional case-based design approaches, this means cases recalled by the system can immediately satisfy, perhaps with some adaptation, the design problem described by the designer. Unless an architect pays attention to how they re-use an old solution a different location, a change of material, or a different client can suddenly mean a solution that was good before is now totally unacceptable. Furthermore, because CBR systems recall case solutions based on their similarity to the problem description and not based on the quality of the solution itself there is no guarantee that what is recalled will actually provide the basis for a workable solution.

Assuming what is recalled is useful for synthesizing a solution for an existing problem, achieving the required adaptation is a very complex process. It is unlikely to use a single case solution. According to Kolodner and Leake (1996):

> "In almost all design problems, more than one case is necessary to solve the problem. Design problems tend to be large, and while one case can be used to solve some of it, it is usually not sufficient for solving the entire problem" p. 56.

Perhaps re-using a "known-to-be-good" solution is better than starting from scratch, but is it truly creative? Can a new design created by "cutting and pasting" an old design or parts of designs together provide an answer when a radical new approach is needed? The investigation of the underlying cognitive processes of creative design using a case-based cognitive model that is associated with CBD development is likely to improve the creativity of case-based systems in the future, but there is still a long way to go. Apart from the practical implementation difficulties discussed previously in this chapter, many developers, including myself, consider trying to create CBR systems that design autonomously is not a worthy or realistic goal.

Legal aspects. There is an obvious advantage for an architectural firm to be able to take better advantage of their own "corporate memory" to save time by reusing standard parts of projects or avoid costly problems through lessons-learned over the years by members of the firm (especially when those people happen to leave the firm). Supporting "corporate memory" is a useful application of CBR systems in design. A more useful CBR system would support "industry memory" and contain a broad variety cases from outside the firms' own experience. The sharing of industry memory and perhaps even corporate memory in architectural practice is, however, somewhat controversial.

The designs architects create are part of their "intellectual property" and by selling this property they make money. The re-use of a complete building design created by another architect is considered to be comparable to plagiarism in writing. Less clear is whether the re-use of parts of a design (or concept) by someone else is a form of plagiarism or how far a design needs to be adapted before it becomes something "new". As CBR systems have not yet been widely adapted into practice it is still unclear whether or not the legal aspects of case re-use may prove to be its "Achilles heel."

Integration. Some designers are concerned computer tools may drive or interfere with the design process. Design support system developers tend to agree that to avoid this problem design tools need to be integrated into one user-friendly environment. In current CBD systems where adaptation is a semi-autonomous process, a human designer is required to use a purpose-built CBR design environment. These environments incorporate a variety tools for topological and dimensional adaptation and case combination, as in FABEL and CADRE. The advantage of such environments is new cases do not have to be entered, but are naturally created through using the system. The disadvantage is some architects may feel limited by the tools available. For the many architects who prefer to use commercial CAD systems they are familiar with, like AutoCAD, it is necessary to integrate or exchange data with the CBR system, which is considerably more difficult.

For CBDA systems that do only retrieval and not adaptation, the issue of integration with CAD is not as critical a problem.

III.3.4. CBDA Systems in Indoor Environment Design

The previous sections show that there are a number of examples of computer systems that use CBR to provide architectural design support. Of these examples, most place emphasis on using the computer to aid or assist in the generation of design solutions as opposed to an advisory or educational role. Not all systems use CBR exclusively. Systems such as FABEL, SEED, CASECAD, and CADSYN include domain knowledge represented separately to design cases either as rules, models or constraints (Maher et al., 1997). Very few CBR design systems address the issue of mechanical engineering and conceptual design development. Four examples are given below.

SEED is a system developed at Carnegie Mellon University to support the early stages of building design through a case-base of different design versions, alternatives and past designs created within its own generative and three dimensional configuration environments (Flemming, Aygen, Coyne, & Snyder, 1998).

Building Design Advisor [BDA] is a program developed at Lawrence Berkley National Laboratory (Papamichael et al., 1997) to support the integrated use of multiple analysis and visualization tools throughout the design process. It is linked to a multimedia web-based Case Studies Database [CSD] that contains information about existing buildings to "provide a realistic context for the specification of performance goals as well as for the evaluation of performance of design alternatives through comparison to real world data" (ibid., p. 351).

ARCHIE and ARCHIE-II (Domeshak, Kolodner and Zimring, 1994) is an extended research program that has produced a number of software systems, all of which have been developed around the concept of creating Case-Based Design Aids [CBDA]. ARCHIE provides evaluative feedback about its cases from a variety of stakeholder perspectives, including mechanical engineering and occupant comfort.

The systems described here use different approaches for using cases to support design. BDA and SEED both include special adaptation environments for recalled cases that largely dictate how a form can be generated. Depending on the designer, this may or may not be too constraining and can add unnecessary detail too early in the (conceptual) design process. Existing outside of any particular design environment, ARCHIE emphasizes lessons to be learned rather than attempting to provide solutions. As such, it relies on a stimulative/learning approach to equip designers with the knowledge required to make their own design solutions. Of the examples provided, ARCHIE's emphasis on the technical *outcome* rather than physical *solution* is the most relevant to the research described herein, as it is consistent with a strategic performance-based design process.

III.4. CBR and Strategic Workplace Design: WEDA

III.4.1. Instrumental Support for Indoor Environment Design

The original inspiration for this doctoral project is a computer tool, but not a CBR or even a KBS system. The Bouw Fysisch Informatie Model [BFIM] (Van Luxemburg, et al. 1994) is a briefing aid for translating building occupant needs into indoor climate performance criteria. BFIM was developed over ten years at the Center for Building Research [CBO] (now known as the Knowledge Center for Buildings and Systems TNO-TU/e). This prototype decision-support system defines indoor environment requirements for residences. The system collects descriptions of the occupant and what tasks they perform in a given space and then calculates performance target values for acoustics (dBA), lighting (LUX), heating (degrees Celcius and PMV), and ventilation systems (litres/second). If one alters the characteristics of the occupant or their activities, such as increasing the age of the occupants or the intensity of work from reading to heavy lifting, the performance targets are then re-calculated accordingly (e.g., increasing light levels, reduced temperature). Originally designed as a Hypercard™ program, BFIM has undergone numerous revisions, ending up as a window's-based application developed in DELPHI.

BFIM is not a true KBS because knowledge in the system (in the form of calculations) is embedded in the software code itself, which makes it difficult for domain experts to maintain and keep the knowledge up-to-date. A lack of transparency means the system is not capable of explaining how it determines the indoor climate requirements it says are necessary. Furthermore, the system does not offer any assistance to the designer in selecting design concepts that can satisfy the indoor requirements it determines. Despite these limitations, BFIM demonstrates a promising approach for establishing initial indoor environment performance criteria for conceptual designs.

By extending and integrating BFIM with a CBR approach I propose to provide the functionality that was missing from the original decision-support system. This new theoretical system, applied to (strategic) workplace rather than residential design, I refer to as "Workplace Environment Design Assistant" or WEDA.

III.4.2. Desired Characteristics for WEDA

WEDA is intended to support early design decision-making by taking advantage of the retrieval and browsing abilities of CBR. As a CBDA, WEDA would not offer solutions for further adaptation by the system or the designer as in CBDs like SEED. The first aim for WEDA is to make technical knowledge accessible and educational. Unlike many of its predecessors, it should be an on-line tool, capable of providing easy access to a multimedia memory of existing and innovative workplace building system precedents generated locally, but shared globally. Many architects cannot recall such projects efficiently on their own partly because there are too many, but primarily because they are likely to come from another design domain — environmental engineering. This differs WEDA from other CBDA systems that concentrate on recalling cases only within the same design discipline.

A second aim is to provide the designer with relevant cases that contain POE information to explore in the context of early strategic performance-based design. This builds on the approaches of earlier CBDAs, such as ARCHIE, that use design outcomes to guide retrieval.

A final aim is to provide up-to-date information by supporting the easy addition of new cases by end-users. This means architects and engineers are able to input case information collected from POEs of buildings in-use without necessarily being computer specialists.

Given these objectives, WEDA's development concentrates on the retrieval, browsing, and case content/storage aspects of CBR. WEDA should provide the following advantages over existing sources of architectural knowledge:

Retrieval. Improve support for memory and technical learning by retrieving a variety of relevant POE cases. Furthermore, allow for one design discipline (architecture) access the knowledge of another design discipline (engineering) through situational assessment — not only to address the differences in vocabulary between architects and indoor environment engineers, but also to deal with a variation in detail and abstraction between early and late design stages — to connect (abstract) conceptual design target specifications with (detailed) POE source cases descriptions.

Browsing. Enhance the opportunistic, explorative aspects of conceptual design (problem-seeking) through (1) an *open non-linear structure* allowing for discovery, (2) *web-based* to make dispersed information accessible at the desktop (3) *multimedia communication* (text, graphics, sound, 3D, animation, video) to explain ideas.

Case storage. Not just a warehouse of post-occupancy information, serve as an up-to-date collective memory that grows and changes over time. The case base is interactive and developable by constituents – not only to consult cases already in the library, but to create new cases, make links between them, and create extra indices.

III.4.3. Measuring the Success of WEDA

> *"Whether an application is accepted by its users strongly depends on whether it is understood by the target user groups, which should be motivated to use the system" (Bergmann et al., 1999).*

Ultimately any software's success or failure hinges on its ease of use and integration with the task. No matter how powerful a tool is, if it is too awkward or difficult to understand it will be discarded. If the system is not useful, or is useful but then its case content becomes outdated, its users are likely to be frustrated and disappointed.

There are some general requirements for improving user-friendliness in KBS systems of any kind. Long lists of questions to answer or forms to fill out should be avoided. Knowledge in the system should be readily accessible so the user is aware of why a certain conclusion is being proposed. The user level should be taken into account to avoid redundancy and improve feedback. Most importantly, knowledge contained within the system needs to be maintained and kept up-to-date. Where possible, the interface should provide a seamless front-end for accessing a variety of tools.

Although it is possible to make a long list of what WEDA *should* be, the best way to know if WEDA (and by implication, a CBR approach) could be truly successful would be to see it and get user feedback. This means not only setting up a clear idea of what the system should do for its intended users (architects), but also developing a prototype system to show to users for feedback.

According to the research of de Groot (1996), a good user interface requires an understanding of people, ergonomics, and visual communication. Of the four techniques described in (Eberts 1994), the combination of two approaches, the *cognitive approach* and *empirical approach*, seems to be the most appropriate for the development of design tools.

In the cognitive approach a user interface is based on an accurate, consistent, and complete description of the computer system and knowledge on how humans perceive, store and retrieve information from short and long term memory. For my project a design process model and support system model for strategic workplace design were created to guide the development of the system and its interface (see Chapter IV).

In the empirical approach a conceptual design is tested among possible users and then is modified and tested again. For my project it was decided to invite users to test WEDA's concept and then the finished prototype in a group decision support environment (see Chapter VII).

III.5. Summary

This chapter introduces Case-Based Reasoning and its application to design. CBR is a computational method used by a Knowledge Based System to solve problems using experience (in the form of cases). The process of CBR involves searching for and retrieving relevant case(s) from case memory and then reusing the case (with or without adaptation) for the solution of a new problem. There are a variety of strategies for representing and storing cases in memory, algorithms for retrieving cases, and techniques for adapting cases. The strategy one chooses to use depends on domain process to be supported.

There are two general types of CBR applications to design, Case-Based Design Aiding and Case-Based Designing. CBDAs concentrate on the support of design decision-making and learning through search and retrieval. Their main task is one of classification and analysis — to use cases to help architects identify the requirements and specifications of design problems, understand design problems, and as a form of inspiration, explanation or instruction. CBD systems involve the identification of solutions. Their main task is synthesis. They use cases (as a representation of previous design experience) as a starting point for the generation of designs for new situations through case adaptation.

The present study concentrates on a CBDA rather than CBD approach not only because it is easier to implement, but also because it is suited to the task at hand. The early strategic design phases produce a definition of the design problem in the form of functional requirements and design constraints that lead to the generation and selection of initial conceptual design solutions. Although synthesis plays a role formulating design requirements, the main interest is to use existing solutions to help architects understand a larger scope of the design problem. More specifically, to help architects understand workplaces from the additional perspective of indoor environmental engineering.

In the previous chapter it was suggested that architects could significantly improve the quality of their early decision-making if they had better support for *memory* and *processing* of technical knowledge. The current chapter has explained how CBDA systems provide support for memory by consistently and more accurately recalling cases. Moreover, since a case-base is not limited to one designer's experience, it should also be possible to create a collective memory from more than one design discipline. Also described is how cases help architects process or understand abstract or complex technical knowledge by engaging and involving them through visual explanation, comparison and contrast, and stories with concrete examples. CBR potentially can put at architects' immediate disposal the technical expertise they have not yet had the opportunity to acquire.

So far, support for the hypothesis that a CBR tool would be very useful for strategic design is based on analysis of the strengths of the CBR process and existing tools reported in domain literature. While there are a few examples of CBR applications that include building engineering topics, there are currently no CBR systems that specifically support strategic workplace environment design. Whether or not a CBR tool would be feasible or useful for supporting this task is difficult to know without actually seeing the system. This is why both the strategic design task and its instrumental support are explored further by implementing a prototype WEDA.

CHAPTER IV

Supporting Workplace Design

Defining Needs and Instrumental Support

This chapter describes the conceptual development of a theoretical CBDA system to support designers during the strategic briefing of workplace environments. Using a typical KBS system development plan as a guide for the research, this chapter addresses questions such as: What would such a system do? What kinds of knowledge would it need? How is this knowledge captured and represented?

IV.1. Introduction

IV.1.1. Implementing a CBDA Support System

Chapter II explained the nature of strategic workplace environment design and its need for computer-based support. It is proposed that architects undertaking early phases of strategic design (briefing and conceptual design) could potentially gain a better understanding of technical issues if they had an easy way to access POEs of existing buildings. Chapter III introduced CBR as a form of computer-based design support and described how it potentially could provide support for strategic workplace design by feeding forward POE information in the form of cases. In order to further establish the conceptual feasibility of supporting strategic workplace design with CBR, it was decided to implement a demonstration prototype CBDA system called Workplace Environment Design Assistant [WEDA].

The following chapters trace the development of WEDA from problem assessment and knowledge and process modelling (this chapter) through case creation (Chapter V) and retrieval (Chapter VI), to programming, as well as validation and testing of the system with a user group (Chapter VII). It should be stated from the outset that WEDA is not intended to be a fully implemented working system, but rather its development is a means of understanding and testing the application of CBR theory to support strategic workplace design.

IV.1.2. System Development Plan

The development of WEDA is divided into six development stages (Figure 4.1.). The outcomes from the various stages in the process are shown on the right hand side of the figure. This process is a hybrid, combining the typical KBS development described in (Durkin, 1994) with that of (TNO, 1996). The process is shown in a linear way for the sake of clarity and scheduling, but in practice it involves iteration and overlap of phases.

IV.2. Problem Assessment

The goal of problem assessment is to provide a more comprehensive definition of the task the proposed case-based system is intended to support. This is achieved by undertaking an analysis of system user (design agent), the activity (strategic design) and the current types of support available for

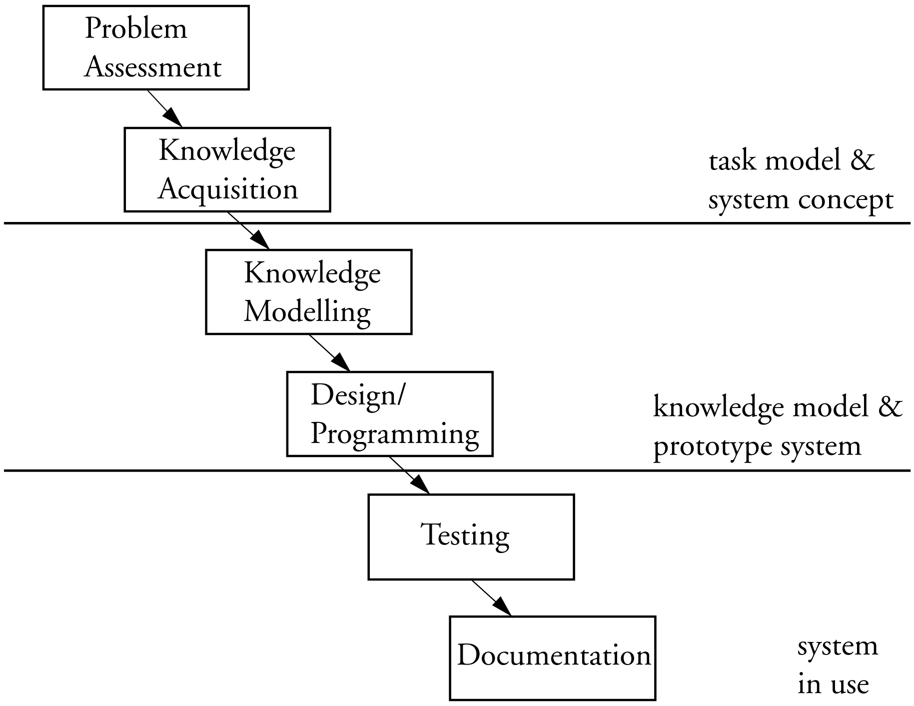


Figure 4.1. System Development Plan

doing that activity (design environment). By understanding the designer and establishing a basic task and support model first, is it then possible to propose a suitable concept for computer-based support.

IV.2.1. The Definition Study

A definition study is the first task undertaken by software engineers to develop KBS computer systems. It typically provides further elaboration of:

1) The problem domain,
2) The problem,
3) Current Solutions,
4) Feasibility and Desirability of a system concept, and
5) System development plan.

The Definition Study that began the research project described herein took a year to complete. As mentioned earlier in Chapter II, the original intention of the project was to implement a design support system for the entire Strategic Building Performance Planning & Evaluation approach [SBPPE]. During the Definition Study a detailed description of what an "ideal" SBPPE support system was created. This proposed system combined various "modules" of computer design support; integrating KBS systems, hypermedia, simulation and database technologies. These modules would work cooperatively with the designer through the SBPPE process. It quickly became apparent that it would be impossible to explore and develop all of the modules within the scope of the current study. The concept of a *case-based support module* emerged, however, as the most promising idea to develop further.

Below are excerpts of the original Definition Study description of WEDA that became the starting point for this project. The complete text of the Definition Study can be found in (Hill, 1997).

IV.2.1.1. The Problem Domain

The development of a prototype case-based support module is part of an overall global effort by our research group to create different on-line modular intelligent tools for supporting technical knowledge acquisition and re-use in building design. Although initially limited in scope to make the project manageable, the possibility should exist for the system to be extended in the future.

What the system will do?

The goal for WEDA is to aid architects in problem representation and preliminary idea selections for a workplace environment concept. It will do this by providing easy access to a case-base of examples and up-to-date knowledge in the field.

How will the System work?

The support system will use case-bases of existing occupant and workplace scenarios and their post-occupancy evaluation data to enter into an interactive dialogue and exploration on the topic of various system concepts that impact on the indoor environment design performance. Key architectural system concepts considered are those concerned with lighting, temperature, acoustics, and air quality issues. Working with this tool should be similar to discussing a problem with an expert that has experience with building system design for many different kinds of workplaces. Based on questions about the architect's design problem, the "expert" should then be able to show the parts of their "portfolio" that contains relevant examples and elaborate on key performance considerations.

Advantages over Existing Tools

This support system will provide an opportunity for designers to access knowledge on-line and on-demand from within their own design environments. By using the system, designers should be able to access knowledge gained through evaluating building designs already in use. The knowledge and cases in the system are located separately from the design environment. Knowledge is updated and maintained collectively by those who use the system (e.g., project team members). Interaction with the system will allow architects to explore information that is normally difficult to remember, or to find, or is dispersed over more than one source.

Risks Involved

The prototype is limited in scope as it is intended to be a module of a greater system. By using the module architects should come away not with solutions, but with a fundamental understanding and some initial ideas of how to address technical issues surrounding the design of workplace environments. Addressing new workplace design situations is never as simple as downloading existing designs. For example, copying or assembling together several "good" examples from the case-library is no guarantee the resulting design concept is good. Building system performance taken out of context requires careful additional evaluation. Exposure in early design to POE cases that have some similarity in context should enable architects to recognize when potential problems are likely to occur and enable them to communicate these concerns to technical consultants on the design team or explore them further with other design tools.

Future User

The prototype system is intended for use by practising architects involved in the early design stages of an office building. The system is based on the use of the Strategic Building Performance Planning and Evaluation methodology. Architects who use the system should also already be comfortable with using computer-aided design and productivity tools in their practice. If case-bases are implemented over the Internet, network connection would be required to use the system.

Desirability

Anticipated benefits from using the system are:

Improved productivity. The system teaches environmental engineering expertise to practitioners within the architectural industry where this technical fluency is lacking. By enhancing current skills and knowledge with the system, better and faster quality decisions can be made about designs for workplaces.

Lower costs. Labour Costs can be directly reduced when the use of a on-line system eliminates the need to pay employees to go out to collect information. Where information is collected for an in-house version of the system, a collective memory is maintained avoiding the loss of expertise and eliminating the need to re-collect data. Indirect savings can also be made through awareness of technical issues acquired by using the system when it helps to avoid errors late in the design process that are costly to revise and correct.

Improved Quality. Improving the skills and knowledge of personnel will improve their work activities and therefore the quality of the services and designs provided by the firm. This tool supports a commitment to continuous improvement, a part of quality control that helps to reduce risk to the client.

Research Contribution. Creating this system could serve to answer several important research questions:

- how to support knowledge re-use between projects
- how to store and acquire knowledge from POE data
- how to share information between domains of architecture and engineering
- how to provide on-line support for the building industry, and
- how to intelligently and accurately retrieve case information according to (dynamic) user needs.

IV.2.2. WEDA System Concept

The results of the Definition Study are summarized in the following statements. WEDA should be:

- **Accessible and Educational.** A web-based CBDA that provides multi-media workplace design cases to inform, illustrate and inspire early design.
- **Relevant.** The designs expertly retrieved based on a capacity to satisfy the functional performance needs of the client.
- **Up-to-date.** Constantly and easily added to by constituents, the case-base contains a wide variety of up-to-date, strategically evaluated designs.

- **Easy-to-use.** Working with WEDA is similar to working with a human engineering consultant. The consultant uses stories and examples of workplace designs from their experience to point out factors that should be considered in solving environmental design problems. The only difference is the engineering consultant would be a computer and their memories would be stored in a case library.

These statements describe a *stimulative*-type CBDA. As explained in Chapter III (sub-Section 2.2.), stimulative CBR systems are used in an interactive manner. These tools use cases to promote creative decision-making and enhance learning about the decision situation as designers work. The designer, not the computer, is responsible for adaptation of selected case concepts into solutions.

In a stimulative-type approach, case representations include more knowledge about the process used to obtain the solutions and reflect the appropriate level of detail for a particular stage of creative decision-making (from preliminary idea selection to refinement of a candidate concept). For example, simply saying that a particular workplace lighting or heating system was a failure is inadequate; the reasons why it was originally chosen and why it ultimately failed must also be included. Ideally the system would be tied into the design decision-making environment (e.g., CAD or Groupware) so that retrieval strategies are triggered by events in the process indicating support is needed, and allow new cases to be added to the case library.

IV.3. Conceptual Modelling

Conceptual modelling is the schematic representation of an information system. According to Dillon and Tan (1993), the key difference between conceptual modelling carried out for conventional software applications and that required for expert or knowledge-based systems is that one needs to model both the *problem space* and the manner in which the *problem solver* tackles the problem. Modelling the problem-solver, in this case a building environment system engineer working with an architect, needs to be limited to the specific problem at hand since it is impossible using current technology to model all aspects of what the problem-solver is capable of doing.

In my study I refer to the model of the problem-solver as the *Process Model* and the model of the problem space (domain) as the *Knowledge Model*.

The Process Model describes a sequence of tasks within the early stages of strategic workplace design. It identifies each process (or task) and its inputs, including when and how cases are used. A process model forms the basis of creating an instrumental *Support Model* – a generic model that guides the development of the computer support and control strategy (i.e., index and retrieval). WEDA's process model is described in sub-Section IV.3.1.

The Knowledge Model organizes the domain knowledge an expert (environmental engineer) uses to support an architect in developing a strategic performance brief and initial ideas for a workplace environment design. Ultimately the Knowledge Model represents what is collected and put in the cases in the case library. WEDA's knowledge model is described in sub-Section IV.3.2. Data models derived from the knowledge model, describe the memory organization and case representation inside the computer. These are explained in Chapter V.

IV.3.1. WEDA Process Modelling

IV.3.1.1. Conceptual Task Model

The conceptual task model presented here represents the behaviour of an architect engaged in strategic briefing within the domain of workplace environment design. Earlier Chapter II described how SBPPE is made up of three main phases: *determine requirements* (strategic briefing), *select system concepts* (conceptual design), and *evaluate & optimise concepts* (performance evaluation). Of these three phases, WEDA is concerned primarily with supporting the first phase, strategic briefing, and helping with the start

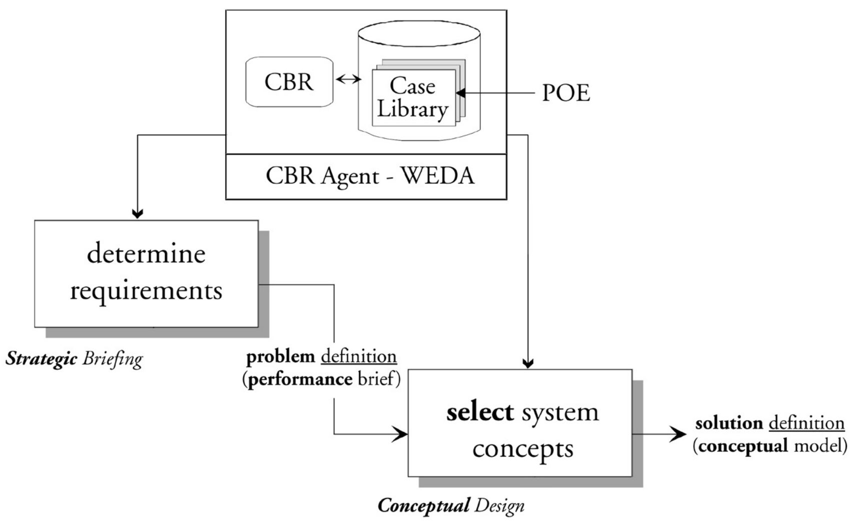


Figure 4.2. Case-Based Support for Strategic Design

of the second, conceptual design (Figure 4.2.). After that, other tools to support conceptual design, such as ILSA (Groot, 1999) would be employed to help the designer.

Part of what an architect might do to solve the technical problem of designing a workplace environment is to attempt to define the problems they wish to solve, and from this come up with some initial conceptual ideas to test that will lead them to solve these problems (or to go back and alter the original problem definition). Strategic briefing is particularly concerned with the task of repetitive problem definition, since one is required for each new scenario.

Within strategic briefing there are five subtasks (Figure 4.3.). For each of these subtasks *products* are identified. For example, during *demand analysis*

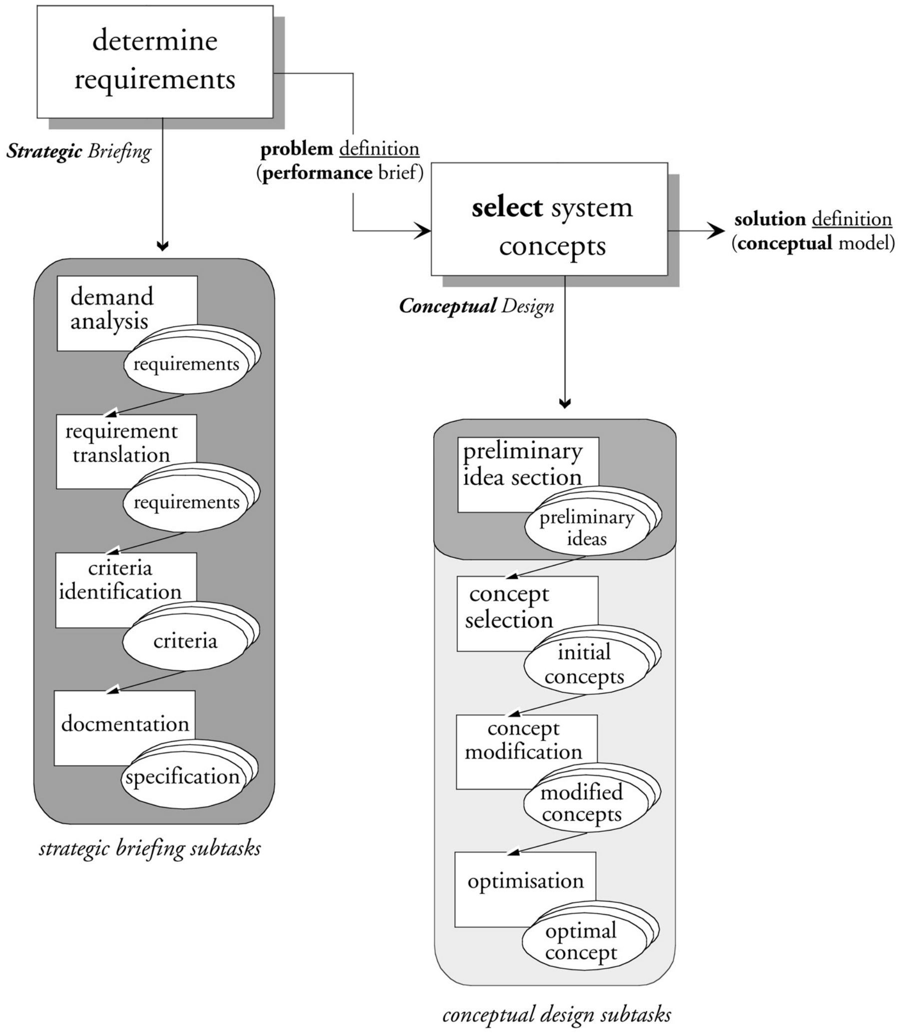


Figure 4.3. Subtasks of Strategic Briefing

an architect will translate an organization's strategic profile into a set of functional requirements (i.e., the architectural brief or program). These basic tasks and products form the basis for creating a process model to determine how WEDA will aid in these tasks.

IV.3.1.2. Process Model

The idea behind process modelling is to "make explicit all the activities (processes), methods, products, resources, and interactions of which software project consists" (Bergmann, Breen, Goker, Manago, & Wess, 1999) p.95. A *process* is a step with a particular goal. Processes transform given input into desired output. A *method* is a particular way in which the process is carried out. To do a particular process certain resources may be required. These can be human resources (or agents) who are actively enacting the process or software tools that are resources used by an agent during the enactment of a process (ibid. p.92). Higher level processes can be further decomposed into sub-processes.

Process modelling for WEDA was done using a structural analysis methodology (Dillon & Tan, 1993). In this method data flow diagrams graphically represent the transfer of data from its source through processing operations. Processes or tasks are shown in circles, objects or "actors" that transmit or receive data appear in squares and diamonds represent tests. Parallel lines or rounded rectangles indicate data. Lines show the flow of data. Dashed lines indicate future links.

The first diagram, Figure 4.4., shows the first level of processes for WEDA. The main process is supporting the *User of WEDA* in *Strategic Briefing* – the development of a specification or *Performance Brief*. This process is supported by four databases of knowledge:

- **Standard Scenarios** – a set of generic organizational profiles,
- **Performance Paths** – relational models for connecting design problems with solutions,
- **Similarity Measures** – strategies for comparisons, thresholds (ranges) and weighting of performance values of indexed variables, and
- **Case Library** – examples of previous solutions and their outcomes.

Other outcomes are lessons and visualizations of the problem and its potential solutions in the form of cases from the case library. Existing *Performance briefs* provide a problem definition and case data retrieved from

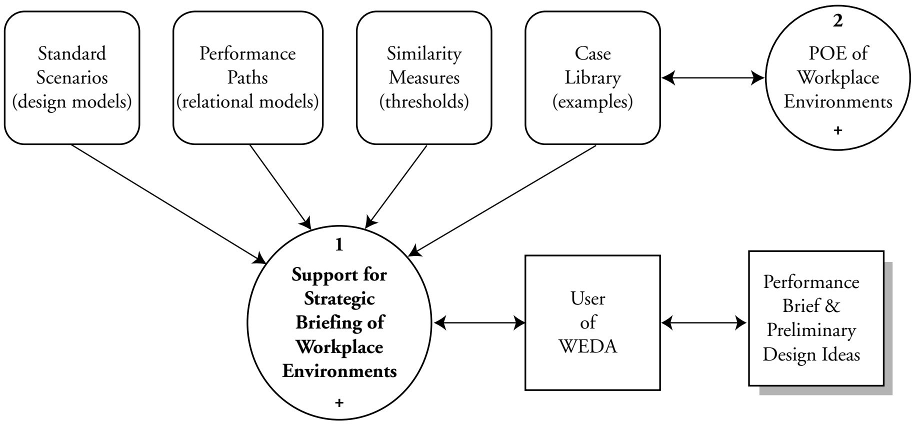


Figure 4.4. First Level of the WEDA Process Model

the case library provide the architect with a deeper understanding of the problem as well as *Preliminary Design Ideas*. New cases for the case library are provided through a second process: *Post-Occupancy Evaluation of Workplace Environments*.

The small plus [+] sign in a process circle indicates the further subdivision of the process. Figure 4.5. is a model showing the sub-processes that occur within the first level process: *Support for Strategic Briefing for Workplace Environments*. This second level process model consists of the five sub-processes (from the task model) with varying relationships to the knowledge stores.

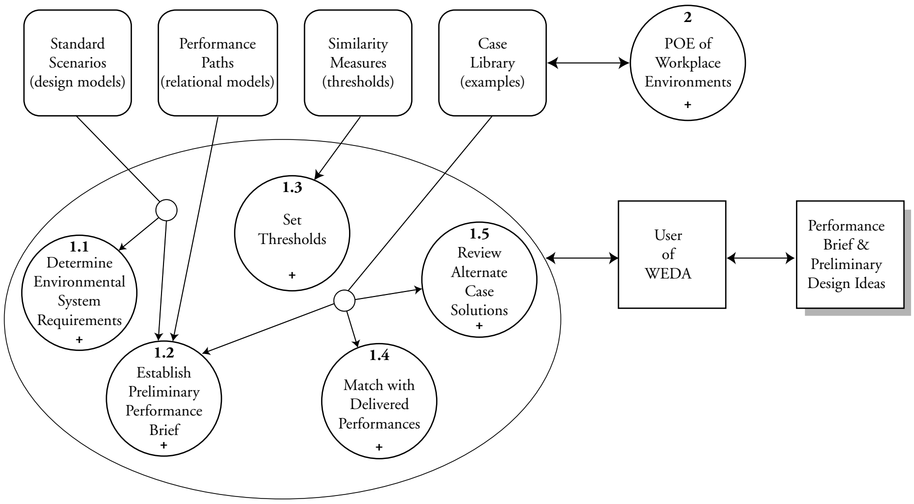


Figure 4.5. Second Level WEDA Process Model:Support for Strategic Briefing

Figure 4.6. is an example of one of the more detailed process models of WEDA where relationship between products, data stores, and sub-processes are shown. At their highest level of abstraction, process models provide a good overview of the purpose of the system. As process models become more detailed (such as the one below) they help to construct the initial software specifications for handling data and supporting potential operations on that data that need to occur within each process step to prepare it for the next.

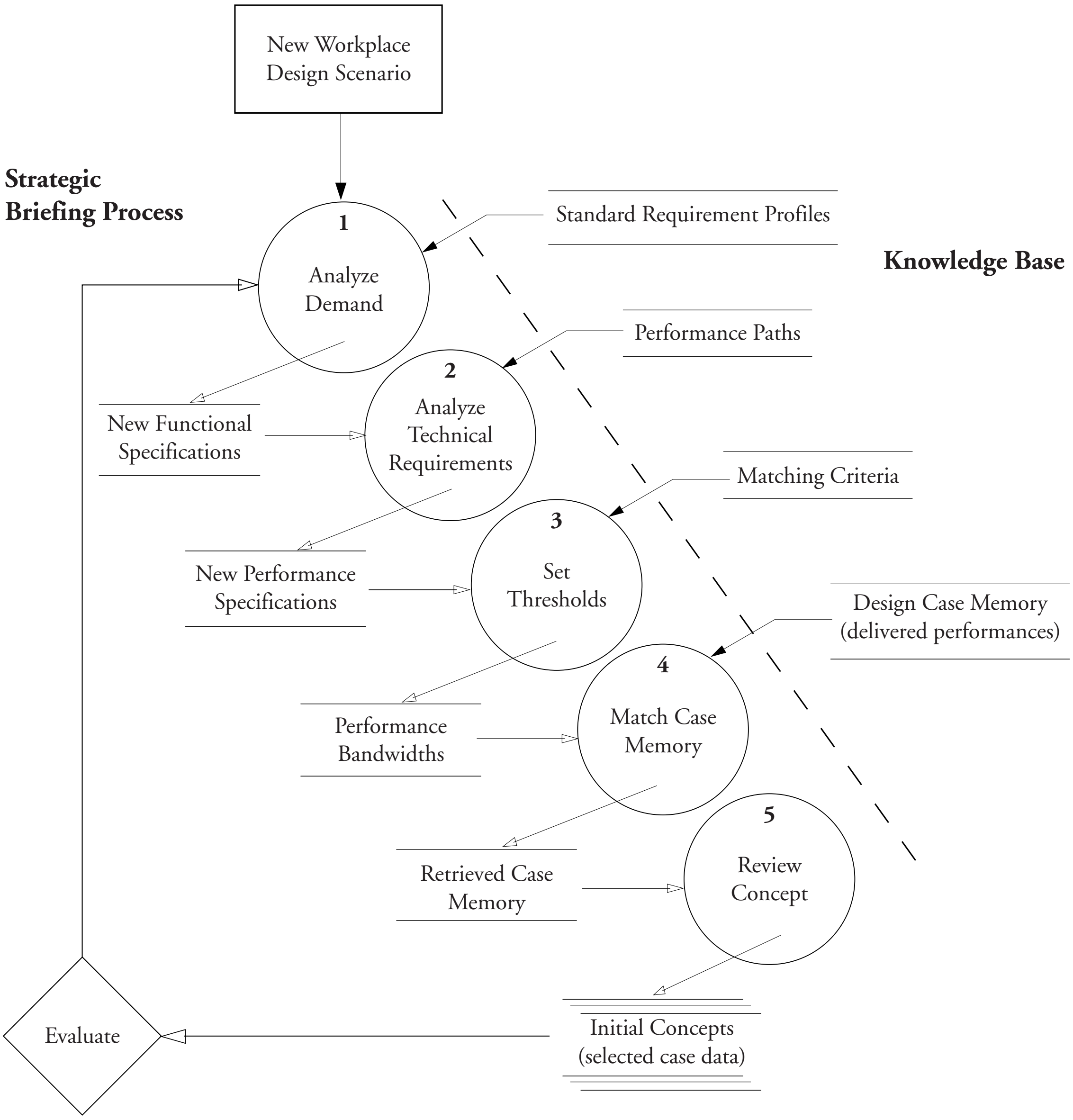


Figure 4.6. Detailed Strategic Briefing Process Model for WEDA

In the process model in Figure 4.6, the *Knowledge Base* provides support to the operations that occur within each process to create: *functional specifications*, *performance specifications*, *performance bandwidths*, and *retrieve cases* from its case library to help the architect establish *initial conceptual ideas*. What kinds of knowledge would these bases contain? How would this knowledge be introduced into these processes?

The process and knowledge models of a design support system are highly related. One describes a series of tasks, and the other describes the knowledge needed to do these tasks. One of the significant challenges of this research was to determine how to capture the knowledge that did the task of relating old design performance outcomes to new design requirements. Part of the answer lay in creating a path.

IV.3.2. WEDA Knowledge Model

IV.3.2.1. Stakeholder Demand Analysis

As described earlier in Chapter III, cases in a conventional CBR system typically contain a description of the *problem* and the *solution* that was used to solve that problem. When retrieving a case, the CBR system compares the description of a new problem with its stored problem descriptions, identifies the most similar one and finds and retrieves its stored solution. The idea is the retrieved solution, because it solved a similar problem in the past, will be the most useful for solving the new problem as well. This conceptual model of CBR assumes there is a direct one-to-one mapping between the problem and solution spaces (Watson, 1997). This poses a particular challenge for representing and retrieving architectural design cases, because there can be more than one solution for any given problem.

In this research the *problem* corresponds to an architectural brief and the *solution* corresponds to a description of an existing workplace environment. To create a CBDA system I need to find out how to connect a current problem (the architect's workplace brief) to the solutions used to solve that problem in the past (POE examples of workplace environmental designs stored in the case-base). For example, how will WEDA know how get from the architect's "10 people using computers" to a case's example of "indirect lighting?" To do this I map *performance paths* between new and old workplace (environmental) design *requirements* and their workplace (environmental control system) design *elements.*

IV.3.2.2. Basic Model Concept

In her 1994 doctoral research on architectural knowledge representation and acquisition, Maha Choukry uses hierarchical relational diagrams to show the relationship between building *requirements* and buildings *elements* involved in the domain of building *change*. I have adapted these knowledge frameworks to identify and describe the relationship between the various *facets* involved in the domain of workplace environment design *performance*.

Chourkry uses her model to show *change paths*. Change paths link human requirements to building elements through measurements of change. In my research I have adapted this modelling strategy to identify *performance paths*. Performance paths link Human System Level *requirements* (demands) to Building System Level *elements* (supply) with measurements of post-occupancy building performance. I call these measures *technical targets* (see Figure 4.7.). Technical targets can be quantitative (e.g., illuminance: 500 LUX) or qualitative (importance of view: "high").

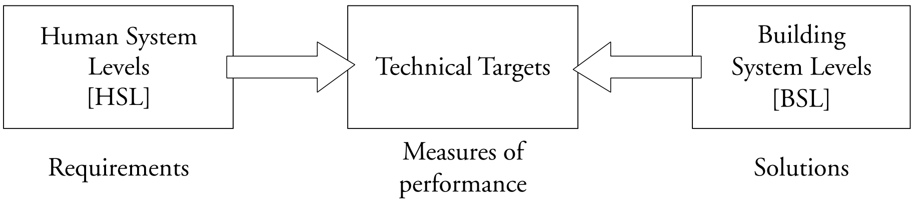


Figure 4.7. Basic Model Concept

Within this model the facets of building performance are decomposed into various levels. The hierarchical levels start with the group level, which is the most global level; move to the cluster level, an intermediate and more detailed level, and end with the item level, the most detailed level. A performance path is defined as a trace of a facet in the hierarchy from a group level entity, via a cluster level entity, to an item level entity that ultimately links to a performance measure (see Figure 4.8.). This is explained in more detail the following sub-Section IV.3.2.3.

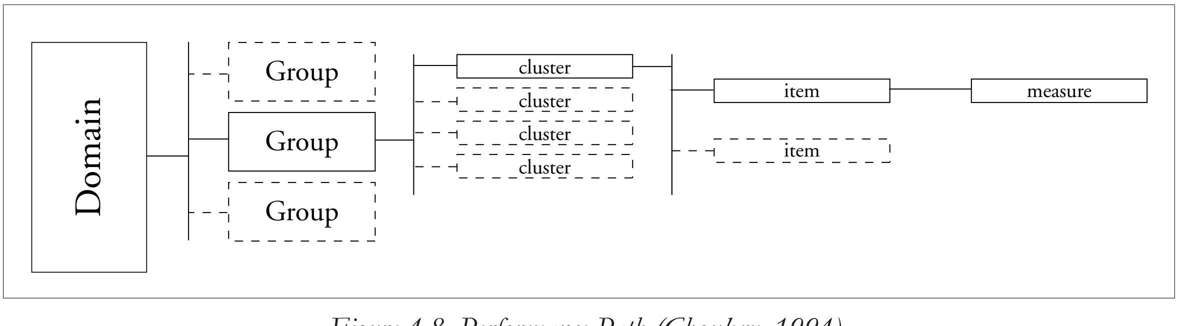


Figure 4.8. Performance Path (Choukry, 1994).

The aim of my model is to represent the requirement-element performance paths within the domain knowledge. The concept is that performance paths would allow the navigation of the domain information from stakeholder demands to design solutions using performance criteria as a "bridge." Ultimately, the models are intended to capture the knowledge needed to teach WEDA how to compare "soft" functionality requirements entered by the User with the "hard" building solutions stored in its case-base. The models also influence what and how both functional requirements and design solutions are represented in the computer (Chapter V).

As shown in Figure 4.9., the scope of the knowledge modelled in this research relates primarily to one "cube" within the entire *building performance evaluation domain matrix* ((Hill, 1997) and Chapter II). The facets within this cube relate to the design performance of environmental control systems (*building services*) in providing individual comfort (*basic well-being*) at the workplace level.

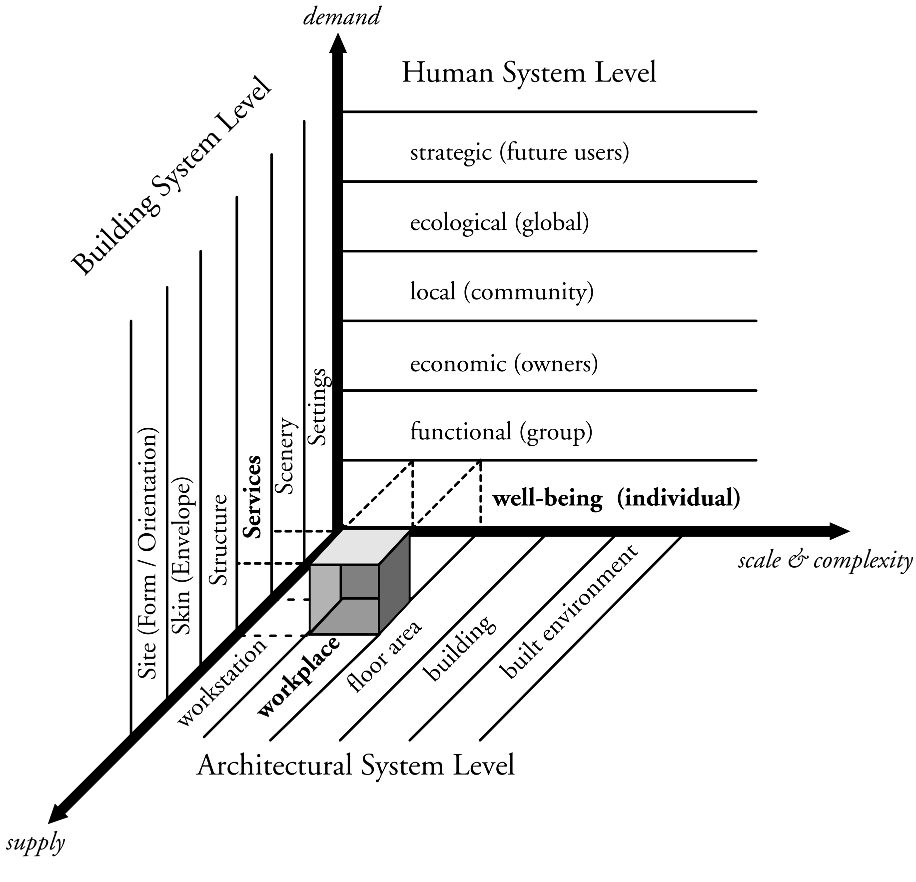


Figure 4.9. Domain of Workplace Environment Evaluation

Knowledge Elicitation. To elicit domain knowledge for the model, an extensive survey of literature relating to the performance evaluation of environmental comfort was undertaken. A variety of publications were consulted, including various books, articles, international and national standards and regulations concerning office buildings and measurement of human comfort. The objective of the survey was to deduce scope and nature of the facets that could adequately describe the performance relationship between stakeholder demand and building supply when it comes to comfort in the workplace.

During the literature survey building service system elements, individual functional requirements, and typical measures of indoor comfort were extracted. The relationships between the facets were then modelled according to the knowledge framework (represented in Figure 4.10.). The results were then validated with domain experts. In this way, several performance paths describing the evaluation of environmental comfort were assembled. This process is described in detail in the following sub-sections through the example of generating a performance path for lighting comfort.

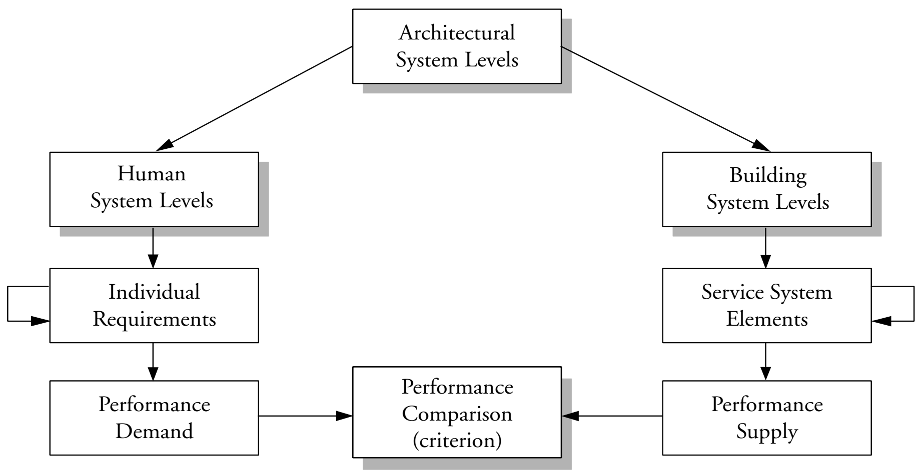


Figure 4.10. Identifying Performance Paths

IV.3.2.3. Performance Requirement Model

The six Human System Levels [HSL] in the domain matrix were modelled into group level entities (right column inTable 4.1.). Each group level entity has its own cluster level requirements. Here the focus is the requirements for the *Well-Being* requirement group. This is because this group is most relevant to workers and workplace environment requirements.

Table 4.1. Performance Requirement Groups

Human System Level	Group Level Requirement
Occupant	**Basic Well-Being**
Group	Functional Value
Owner	Economic Value
Community	Local Value
Global	Ecological Value
Future	Strategic Value

Table 4.2. shows how the "Well-Being" entity was modelled into 4 cluster entities that influence the well-being of human beings: (*Well-Being: health and comfort)*, *(Well-Being: safety and security*), *(Well-Being: spatial quality*), and *(Well-Being: shelter).* The *(Well-Being: health and comfort)* cluster includes requirements related to indoor climate such as thermal comfort and air quality. *(Well-Being: safety and security)* cluster entities relate to requirements such as way-finding, accessibility, fire protection. *(Well-Being:spatial quality)* cluster entities relate to requirements such functionality, flexibility, and aesthetics. *(Well-Being:shelter*) cluster entities relate to the need for a building to protect occupants from exterior elements such as moisture, wind, and sun.

Table 4.2. Well-Being Requirement Clusters

Group Level Requirement	Cluster Level Requirements
Well-Being	**Health & Comfort** Safety & security Spatial quality Shelter

Of the 4 cluster level requirements, *(Well-being : health &comfort)* was detailed further into item level requirements of *(Well-being: health & comfort: thermal/hygric comfort*), *(Well-being: health & comfort: acoustic comfort*), *(Well-being: health & comfort: air quality*), and *(Well-being: health & comfort: visual comfort*). These are shown in Table 4.3. – Well-Being Requirement Items.

Item level requirements are used to determine target level for technical performance. For example: the required visual comfort is interpreted into a lighting level for a workplace (measured in horizontal illuminance or [LUX]) as shown in Table 4.4..

The performance requirement model defines what the performance requirement is, as well as tells us a way of expressing the level of performance required in a measurable form. As such, the model provides us with a powerful way of understanding the facets of building performance requirements.

Table 4.3. Well-Being Requirement Items

Group Level Requirement	Cluster level requirements	Item level requirements
Well-Being	**Health & Comfort**	**Visual Comfort** Thermal/Hygric Comfort Acoustic Comfort Air Quality Spatial Comfort Building Integrity

Table 4.4. Technical Performance Target (Visual Comfort)

Group Level Requirement	Cluster level requirements	Item level requirements	Technical Performance Target
Well-Being	Health & Comfort	Visual Comfort	Illuminance [LUX]

IV.3.2.4. Element Performance Model

The physical components of a building or "elements" are modelled in the same way as the requirements. The group level is divided into six Building System Levels [BSL]: *Stuff*, *Space Plan*, *Services*, *Skin*, *Structure*, and *Site* (see Table 4.5. and Chapter II). It is important to note that building entities, though divided into performance groups, are heavily interdependent. Dividing buildings into element groups makes it easier to identify a particular performance path. This same element, however, can be associated with another performance path.

Table 4.5. Element Group Entities

Group Level Element
Stuff Space Plan Services Skin Structure Site

Knowledge related to indoor environments is found in both the *Services* and *Skin* groups. The Services group is defined as the set of systems providing services to the building. The subsystems that make up the cluster level (shown in Table 4.6.) are: (*Services: Heating Ventilation and Air Conditioning [HVAC]*), (*Services: lighting*), (*Services: controls*), (*Services: water*), (*Services: sewage*), (*Services: power*) (*Services: communication*), (*Services: security*), and (*Services: conveyance* e.g., elevators and/or escalators). Services element cluster entities refer to active (mechanical) systems. Environmental systems can also be passive such as an air supply through natural ventilation or lighting through daylighting. As part of the building envelope, these systems are referred to in the Skin group clusters such as (*Skin: openings*), (*Skin: sun shading*).

Table 4.6. Services Element Cluster

Group Level Element	Cluster level Element
Services	**Lighting System** HVAC System Water System Sewage System Power System Communication System Security System Conveyance System

Item element entities are subsystems of cluster entities and are intended to represent those elements that have the most direct impact on the technical target (performance criteria). The example in Table 4.7. shows how an element of an electrical lighting system concept is linked to a technical target.

Table 4.7. Example of Element Performance Model

Group Level Elementt	Cluster level Element	Item level Element	Technical Performance Target
Services	Lighting System	Light Source (lamp)	Illuminance [LUX]

IV.3.2.5. Performance Path Model

By linking together requirement and element performance models I establish a *performance path*. Table 4.8. shows the performance path established between the requirement "Occupant Well-Being" and the elements of a "Building

Table 4.8. Performance path model for lighting

Group Requirement [HSL]	Cluster Reqt.	Item Reqt.	Technical Target	Item Element	Cluster Element	Group Element [BSL]
Occupant Well-Being	Health & Comfort	Visual Comfort	**Task Illuminance [LUX]**	Light Source (lamp)	Artificial Lighting	Services
Requirements →				**← Solutions**		

Service" solution. Technical Targets (measurable performance criteria) act as a "bridge" between requirements and building solution perspectives. This is easiest to see in graphical format as shown in Figure 4.11..

This performance path begins with a general entity "Occupant Well-Being" moves through "Health & Comfort" and "Visual Comfort" and ends with the required performance measure "Task Illuminance." Similarly, general building "Services Systems" is decomposed into elements of the solution through "artificial lighting" to "light source" that provides a measurable performance of "illuminance."

The performance path discussed here is just one of several paths relating to indoor comfort developed through my study. Viewed together as shown in Figure 4.12., the resulting network of pathways bridged by fifteen technical targets reveals the complexity and overlapping nature of the performance relationships.

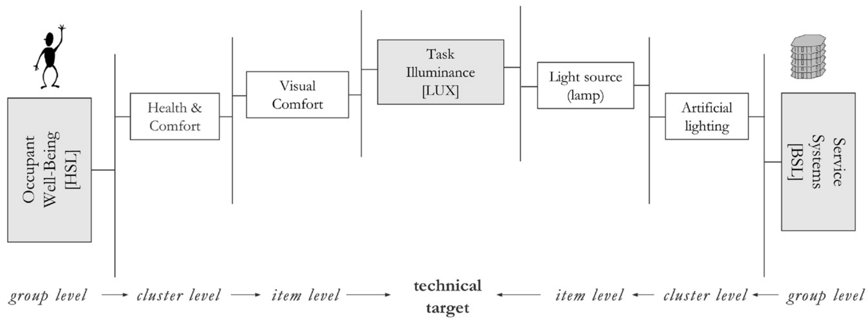


Figure 4.11. Graphic Depiction of a Performance Path

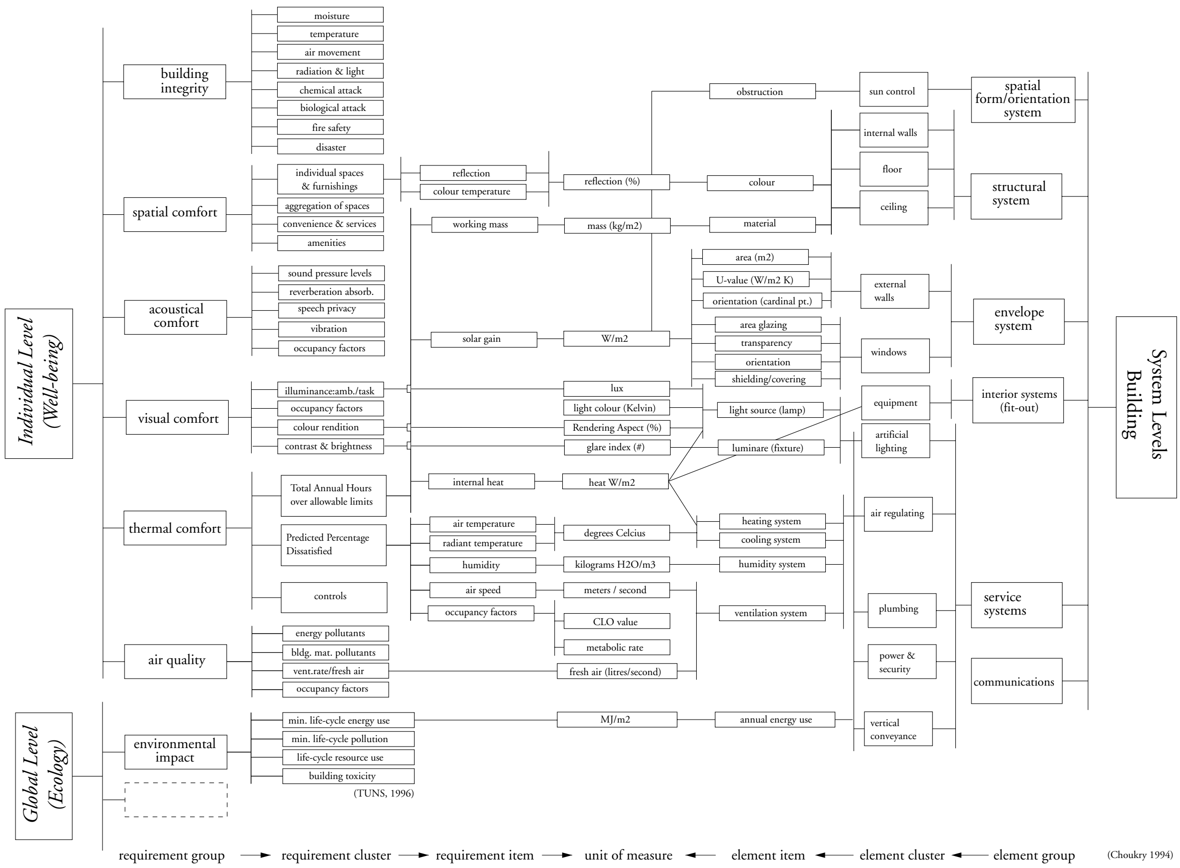


Figure 4.12. Multiple Performance Paths of Workplace Comfort

IV.3.4. Multiple Performance Criteria

The *requirement-element* model described in the previous sections suggests that requirements and elements can be linked by a single technical target. The actual measurement of building performance is much more complex. Establishing building performance always requires multiple criteria evaluation. This is why the knowledge representation model needs to be taken a step further.

During the literature survey several POE methods used within the domain of environmental engineering for the cluster *(Well-being:Health&Comfort)* were reviewed. Each method uses a set of multiple criteria to establish the level of performance of a workplace environment system.

Analysis of the POE methods relating to the measurement of *Health & Comfort* consisted of identifying technical targets (performance criteria) were identified for each *item level* of the cluster: *visual*, *thermal/hygric*, *acoustical*, and *air quality* (Figure 4.13.). The original purpose of my investigation was to determine a single technical target to best describe the performance of a

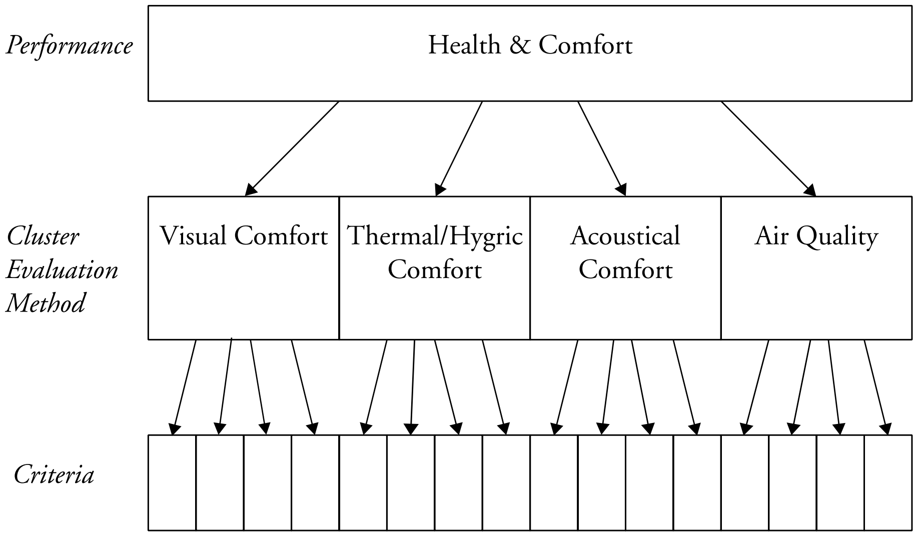


Figure 4.13. Evaluation Models

case for each environmental comfort requirement. The findings were that a performance description did not consist of a single criterion, but required sets of multiple performance criteria.

IV.3.4.1. Multi-Criteria Requirement-Element Model

Modelling the performance of buildings is incredibly difficult. It requires identifying the various building elements that contribute to the capability of a building environment perform well in relation to a specified requirement. For example, the performance of the lighting system will depend, in part, on the colour of the paint and the light absorbency of the carpet (International Center for Facilities, 1994).

To overcome this problem I have adopted ASTM/AINSI's Serviceability Tools and Methods [ST&M] use of matched scales to extend my model of the relationship between occupant requirements and building descriptions. Like the *requirement-element* model, ST&M has user requirement linked to building descriptions. Unlike the *requirement-element* model, ST&M links together multiple requirements with multiple building *performances*.

The ST&M model consists of tables with two matching scales. Each scale contains five descriptions. The "supply" scale description defines the level of functional requirements required by stakeholders. It describes stakeholder needs in everyday language. The "demand" scale is used to rate the capacity of a facility to meet a particular range of performances. It describes buildings in performance language. Each scale identifies levels of quality calibrated from 1 (less) to 9 (more) (see Table 4.9.) (Davis & Szigeti, 1996).

Table 4.9. Davis ST&M Scale Model

Demand Description		Supply Description
Highest level of quality	9	Highest level of building
—	—	—
—	—	—
Lowest level of quality	0	Lowest level of building

The strategy of grouping stakeholder requirements and building performance descriptions by levels of quality is easy to understand for both stakeholders and design professionals. The natural language and performance descriptions used in the ST&M scales, however, cannot be directly automated. To create my knowledge models, I modified this representation approach, separating out the individual requirements and building performances, but maintaining the overall grouping by quality levels (see Table 4.10.).

Table 4.10. Adapted (Multiple-Attribute) Scale Model

Demand (Requirements)			Level	Supply (Target Performances)		
R_1	R_2	R_3	9	T_1	T_2	T_3
-	-	-	-	-	-	-
-	-	-	-	-	-	-
R_1	R_2	R_3	0	T_1	T_2	T_3

Each matching set of supply-demand scales in ST&M relate to different topics. The scales relating most directly to my study fall under two ST&M topics: *A.3. Sound & Visual Environment*, and *A.4. Thermal Environment and Indoor Air*. These are found under the general category of *A. Group and Individual Effectiveness.*

I used the ST&M approach to create matching multi-attribute scales for various aspects of workplace indoor environment design. The matching scales for the topic "lighting" are shown in Figure 4.14.. The requirements and performance criteria used in the scales come from not only ST&M, but also various building performance evaluation models. The example shown in Figure 4.15. includes additional criteria based on IESNA's method for establishing visual comfort. All of the resulting scales were validated with a domain expert.

The content of the ST&M scales are a good source of evaluation expertise, but to elicit knowledge for my models I needed to draw upon other sources as well. The ST&M scales incorporate both ASTM and American National Standards [AINSI] and the latest version (2003) is on the verge of becoming

Demand (Requirements) Lighting			**Level**	**Supply (Target Performances) Lighting**				
$\mathbf{R_1}$ Occupant Task	$\mathbf{R_2}$ VDU Use	$\mathbf{R_3}$ Tolerance Lighting Defects		$\mathbf{T_1}$ Illumination Level [LUX]	$\mathbf{T_2}$ Control	$\mathbf{T_3}$ Visual Defects	$\mathbf{T_4}$ Glare	$\mathbf{T_4}$ Personal Glare Control
Different Everywhere	VDU & Paper	None	**9**	300-700	Flexible	None	None	All
Different in Parts	Long periods VDU	Low	**7**	300-700	Adaptable	None	Some	Possible No cost
Single Visual Task	Several VDUs	Medium	**5**	500-700	Fixed	1	Yes	Possible Small cost
Non-visually demanding	Few VDUs	High	**3**	700-1000 or 0-300	Fixed	2	Yes	40-60% Stations None
Minimum Requirement			**1**	700-1000 or 0-300	Fixed	≥3	All	None

Figure 4.14. Simplified Example of New Multi-Requirement-Element Model for Lighting

part of international standards (i.e. ISO/TC and French Government CSTB). I found that both the demand and supply descriptions used to evaluate the environmental quality of workplaces in the 1996 ST&M scales available at the time of my study, however, relate quite heavily to North American-style office buildings. In Northern Europe there are many more regulatory requirements relating to the well-being of the individual worker such as, access to daylight, natural ventilation, and minimum floors areas per person, that have a great impact on the design and configuration of office buildings. Deep depth buildings with large area "cubicle farms" are less common in Northern Europe. In my models I have incorporated additional criteria based on local (e.g., Dutch – ARBO) and European standards and building evaluation methodologies (e.g., CIBSE and ISO) in order to try to accommodate the small 1-2 occupant offices typically found in existing office buildings in Northern Europe, and newer approaches to office design such as combi-offices (group and individual space offices) and task-based "flexible" or "agile" workspaces.

Although I have chosen to base my knowledge models on certain building environment evaluation methods selected from existing POE approaches and American ASTM/ASHRAE and European CIBSE Standards (see also Chapter V), these methods are by no means the only, or possibly even the best, methods available. Unfortunately, there is no single universally agreed upon method for the evaluation of indoor environments. Some methods of evaluation, such as Fanger's Method for evaluating thermal comfort, are controversial and others, such as a financial model of comfort, simply do not exist. Since it is not the intention of this research to generate or validate evaluation methods, I have tried to work with methods already available and in-use in practice. The beauty of the knowledge modelling approach described here is that it can be used to represent a variety of approaches.

IV.5. Chapter Summary

This chapter discussed the conceptual modelling of a theoretical CBDA system called the Workplace Environment Design Assistant or WEDA. The aim of WEDA is to allow architects to access multi-media workplace design cases to inform, illustrate and inspire early strategic design. The purpose of conceptual modelling is to determine the basis by which such a system would provide support. This includes studying the nature of the task that will be supported, the types of support provided, and from this determine a layout of a CBDA-tool that meets these requirements.

Based on my analysis of the nature of strategic design it should be possible to support designers in the initial generation of a performance brief and preliminary design ideas where the system permits:

- support for the translation of functional design requirements into technical design requirements,
- performance feedback, providing specific examples that explain the level of serviceability of a building system, and
- on-demand access to relevant examples, providing assessment of the suitability of building systems represented in the case library in relation to functionality requirements.

Following the articulation of the task and its underlying knowledge requirements, it is necessary to focus on understanding the nature and scope of the domain knowledge itself. This was achieved in my study through an extensive survey of domain literature concerning building performance evaluation. Through analysis and modelling, I have demonstrated how it is possible to connect a new design problem to the solutions used to solve that problem in the past using multi-criteria performance paths.

This chapter mainly addressed the representation and acquisition of “control” knowledge – the knowledge that dictates: “how to process and feed-forward design information” (performance paths and multi-criteria performance analysis). Chapter V introduces a methodology for the acquisition of the “content” knowledge – the collection, compilation and representation of workplace environment cases.

CHAPTER V

Capturing Design Knowledge

Creating Workplace Cases

This chapter examines the role of Post-occupancy Evaluations [POE] in providing information for a case-based workplace environment design support system. A CBR system can be very helpful to designers, but only if the cases are useful. This means being able to provide a good selection of interesting and up-to-date cases. What should be in a case to support strategic workplace design? To begin to address this question, a POE toolkit is created and a series of POEs are undertaken of existing workplaces and then placed in a case library. Based on this experience, a method is proposed for how to classify, collect, and represent workplace environment data.

V.1. Making a Case for Workplace Quality

Cases are the fundamental part of any case-based reasoning system. Without cases a CBR system would not have any expertise at all. Having developed process and knowledge models for WEDA (see Chapter IV) the next task is to collect case data from real workplaces in-use.

Previous studies do not explain what should be in a workplace environment case, nor do they explain how to collect and represent workplace data into a CBR system. If the data required by WEDA would be impossible or difficult to collect or store, then the system would be very hard to maintain. Until the types of workplace data strategic design might require are considered, collected and placed in a case library, it would be impossible to fully understand how maintainable the knowledge would be. Finding answers to these questions was undertaken through a combination of POE literature analysis, field work, and consultation with domain experts.

V.2. What should be in a Workplace Case?

It is not surprising the first issue confronted with in trying to create a case-base for WEDA was: "What is in a workplace design case?"

A generic design case for a CBR system, as introduced in Chapter III, always contains a *problem* and *solution* description. Here I will refine that definition further to support a performance-based approach. In a performance-based approach architects not only need a description of a particular design problem and the solution selected for it, but they also need to know: "how well did the design solution perform in-use?"

Performance evaluation is represented in the 3D domain model (Chapter II) as the intersection between Human System Level [HSL] (requirement)

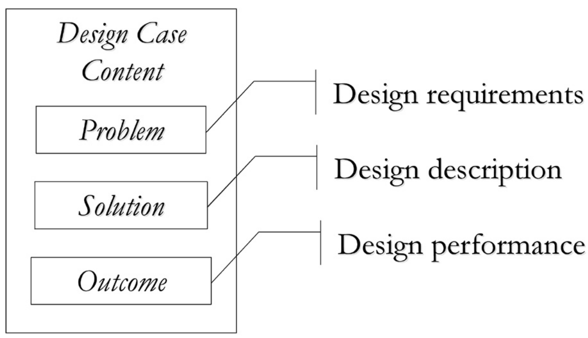


Figure 5.1. Overview of a Performance-Based Design Case

and Building System Level [BSL] (element) at a particular Architectural System level [ASL] (scale/location). At this intersection the outcome of the building system is assessed according to certain performance criteria. A performance-based design case is a record containing three aspects (Figure 5.1.):

1) Problem (design demand requirements)
2) Solution (design description), and
3) Outcome (design performance)

For example, a workplace case *problem* can be that all of the occupants use computers and cannot tolerate any glare from lighting on their screens. The *solution* used is an indirect lighting system. The performance *outcome* of the indirect lighting is assessed by measuring the amount of glare on the screens in the workplace to see if it is within acceptable limits.

While collecting real case data I realized performance is not simply a question of measuring physical performance. Some aspects, such as effects of lighting year round, can only be practically known through simulation. Other aspects, such as user perception, can totally outweigh whatever other physical evidence you may have that says a system is good. In response, I have further divided the outcome aspect of case content into four components that I refer to as the "MOPS model of outcome" (Figure 5.2.):

1) **M**easured outcome (physical behaviour)
2) **O**bserved outcome (expert's opinion and occupant behaviour)
3) **P**erceived outcome (occupant opinion), and
4) **S**imulated outcome (calculated behaviour).

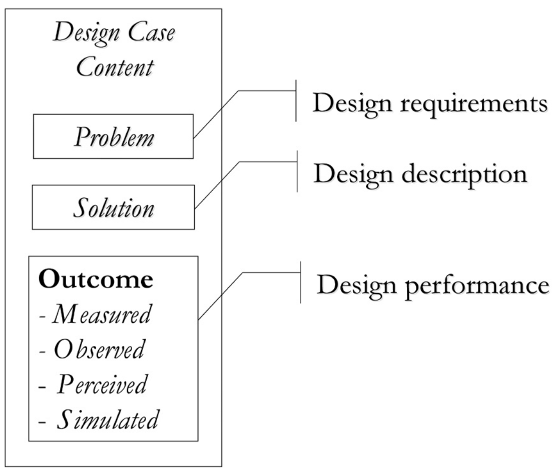


Figure 5.2. MOPS model of outcomes

V.2.1. Scope of Study

The 3D model introduced in Chapter II, describes the entire knowledge domain of the *Performance Evaluation of Office Buildings*. Cases used in a fully implemented CBR system to support a performance-based building design process would encompass all the information contained within the 3D domain model. Acquiring case content for WEDA focuses on a portion of the domain model relating to evaluating Health & Comfort in the workplace: *Visual Comfort*, *Thermal/Hygric Comfort*, *Air Quality* and *Acoustic Comfort* (Figure 5.3.). This focus area was chosen because improving environmental satisfaction impacts on key business drivers for workplace clients: employee output and productivity.

POE data was collected from five cellular offices and three workplaces. These particular cases were selected because all of them involve innovation in design. The cellular offices are examples of the use of innovative service systems in standard office layouts. The workplaces are examples of the use of innovative office layouts in areas with standard building services. In this way, I was able to gain a good understanding of the nature of post-occupancy data collection as well as assemble a representative sample of interesting workplace environment data to begin a case library.

V.2.2. Environmental Comfort Performance Criteria

Environmental comfort in a workplace is defined in many ways, but it is essentially about avoiding *metabolic imbalance*. People should not be overheated, overcooled, have excessively varying air or radiant temperatures (e.g., from windows), have enough removal of old air and supply of fresh air, have enough light but not too much light so that it causes glare (ESRU, 2002). Acoustic balance is also important. Too much information-carrying sound or sound from outside the building and people become distracted, too quiet and even the slightest sound seems amplified. In practice, the best environment is one that occupants do not notice at all. Or, if they do notice it, they have the ability to individually control or get rapid response to change environmental settings to desired levels.

Performance evaluations done in my study are based on criteria drawn from a survey of domain literature about workplace environment systems evaluation. My survey included evaluation models from professional associations (e.g., IESNA, ASHRAE), international building codes and standards (e.g., ISSO, ASTM, NEN), governmental and private organizations (e.g., Building-in-Use, RGB, DEGW) and consultations with individual experts specializing in lighting, acoustics, and HVAC systems.

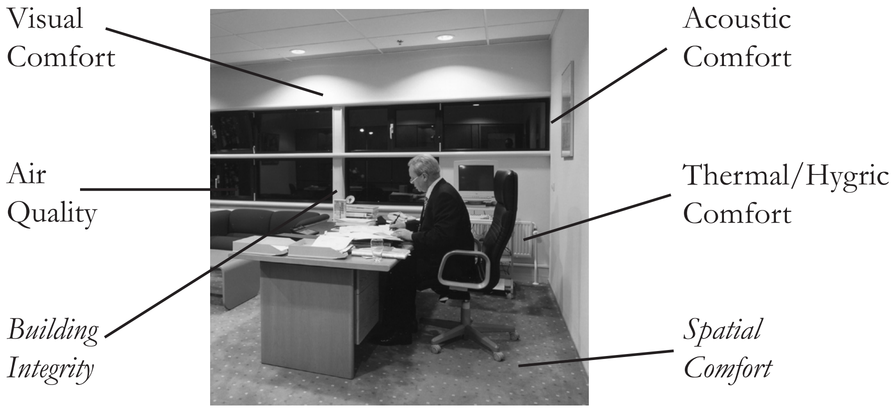


Figure 5.3. Workplace Enviornment Comfort Factor

The seventy-seven criteria selected to represent *case outcome* consists of a cross-section of physical, perceptual, behavioural and simulated performance measures for each comfort area (see Table 5.1.). Over one hundred and fifty attributes were also selected to describe the original *case problem* (design requirements) and *case solution* (design elements) for each case. More attributes for lighting are identified than for any of the other categories. This is due to the significance of lighting in the majority of the workplaces studied and the local availability of expertise. It was also important to include these attributes so WEDA could work with its sister system, ILSA (Integrated Lighting System Assistant) (Groot, 1999) that was being developed simultaneously.

Different methods were assembled to determine performance in relation to each criterion. The resulting "toolkit" of data collection methods is discussed in detail in the following Section V.3.

V.3. Collecting Case Data using POE Tools

Post-Occupancy Evaluation [POE] is the activity of evaluating buildings once they are in-use. POEs concluding the success or failure of a particular design solution, combined with recommendations for improvement, are typically used for immediate feedback to the client/owner. POE is also used to inform the building industry to aid improving the performance of similar building types as well as used to establish general guidelines and standards. This makes POE an obvious source for tools to collect and analyze data to form cases for a case-based system.

According to Preiser, Rabinowitz, and White (1988a), there are different levels of POE investigations, from *indicative*, showing only major building

Table 5.1. Environmental Performance Evaluation Criteria

	Visual Comfort	Thermal Comfort & Air Quality	Acoustic Comfort
Physical	Task_illumination_level Vertical_illumination_level Reflection_factor_floor Reflection_factor_walls Reflection_factor_ceiling Lamp_colour_temperature Rendering_factor Lighting_power_consumption Work_area_photograph	Air_temperature Relative_Humidity Air_velocity Thermal_radiation Ventilation_flow C0$_2$_level Ventilation_rate Ratio_Dust_particles	Sound_pressure_level Problem_sound_sample
Observed	Panorama_image Daylight_contribution Visual_defects Disability_glare Discomfort_glare VDU_veiling_reflection View_quality Ease_of_relocating_lights Workstations_≤7m_from_Window Observer_lighting_story	Environmental_adaptations Observer_thermal_story Observer_air_quality_story	Internal_sound External_sound Information_carrying_sound Observer_acoustic_story
Perceived	Glare_sun_sky Glare_artificial_light Electric_lighting_ Quality_view_outside Visible_text_size Overall_lighting_satisfaction Overall_lighting_importance Occupant_lighting_story	Air_temperature_winter Air_termperature_summer Air_movement_winter Air_movement_summer Occupant_thermal_story Overall_air_quality_summer Overall_air_quality_winter Occupant_air_quality_story	Distraction_noise Overall_speech_privacy Importance_speech_privacy Overall_acoustic_satisfaction Importance_acoustic_to_task Occupant_noise_story Occupant_speech_privacy_story
Simulated	Room_Perspective_Rendering Cross_Section_Rendering Plan_Rendering Side_Wall_Rendering Rear_Wall_Rendering Daylight_Factor_Distribution_Plan Daylight_Factor_Distribution_Section False_Colour_Image	Air_Flow_Simulation Predicted_Mean_Vote	
General	Level_of_personal_control Frequency_use_personal_control Achieve_desired_conditions Self_reported_productivity Overall_comfort Overall_meet_needs Most_positive_features Most_negative_negative		

successes and failures, to *diagnostic* investigations that are very in-depth and comprehensive. The level of POE used here is *investigative*. This is an intermediate form of POE investigation. Unlike the indicative approach, which relies on the experience of the evaluator for performance criteria, the investigative method uses research-based criteria explicitly stated before the building is evaluated. Even though this means more resources are required for literature assessment and a higher sophistication of data collection and analysis, the advantage of using research-based criteria is data can be more easily compared between similar facilities. Since the objective of my data collection is to feed-forward into the future projects, comparability is an important feature. Usually an investigative POE will consider criteria from a variety of topics (for example: image, security, energy, etc.). In my study, the criteria are limited to indoor environments. This meant my POE would not be as time-consuming and require as many resources as usually needed to undertake a typical investigative POE.

My search for an ideal POE methodology quickly revealed there is no single, universally accepted method for collecting and analyzing building environments. Left with two options: creating a totally new set of collection tools or adopting those of others, I chose to adopt existing POE methods into a specialized "toolkit" for evaluating indoor environmental comfort.

V.3.1. Philosophy of theToolkit

The POE toolkit used in my research has been developed with a particular philosophy in mind — the methods developed to capture on-site data should be relatively inexpensive, portable, and easy-to-do. Making environmental data collection as straightforward as possible is important for maintaining WEDA's case library. If I could develop collection methods that were simple yet accurate enough, it is conceivable that more architects would be able to do POE's of their own buildings, and consequently create their own cases to put into a case library.

Another important philosophy was to create a method that allowed for the multi-dimensional evaluation of workplace environment quality across a variety of qualitative and quantitative measures. Boyce and Eklund (1995) argue that although some approaches suggest that environmental quality can be reduced to a few single number indexes, this inevitably leads to a loss of information. A richness in collected information increases its flexibility for re-use.

V.3.2. A POE Toolkit for Collecting Workplace Comfort Data

How can information relating to a design brief, design solution, and outcome information be collected from workplaces in-use? This section discusses the development and application of the special POE toolkit designed as part of my study for evaluating office comfort on the dimensions of visual, thermal, acoustic and air quality. The tookit is summarized in Table 5.2. It consists of existing POE data gathering tools and approaches adapted to collect workplace environment case data. Each tool within the toolkit is described in further detail in the following sub-Sections.

Table 5.2. POE "toolkit"

		POE Tools				
	Chapter Section	3.2.1.	3.2.2.	3.2.3.	3.2.4.	3.2.5.
Case Component	Attribute-Value Source	Document Analysis	Physical Monitoring & Measurement	Simulation (Calculation & Modelling)	Observation Studies	Occupant Survey / Interviews
Problem Description	Requirements	●				●
Solution Description	Design	●			●	
Performance Outcomes						
Measured	Quantitative —physical	●	●			
Observed	Qualitative — experts				●	
Perceived	Qualitative —occupant/ group					●
Simulated	Quantitative — calculated			●		

V.3.2.1. Document Analysis

The analysis of existing documents is the starting point for most POE investigations. It is a general process and relatively inexpensive. It is the source of the original design description, including the goals of the original design and later development and renovations. It also includes the physical description of the solution, and in particular, the specifications about the installed building environment systems.

As-built drawings of a facility are particularly useful. Evaluating the building plans first can already tell a lot about potential building-related comfort problems. For example, where occupants are near a window, structural or ventilation shaft there may be more problems. As-built drawings are also essential for navigating and note-taking in physical and observational studies, not to mention providing dimensional information for computer simulation studies. If existing design solution data is available in digital form it can

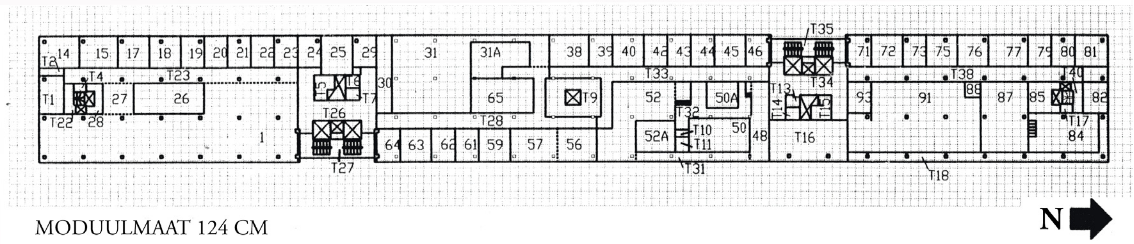


Figure 5.4. As-built Floor Plan of 10th Floor Case Rooms

form part of (default) information for inputting into simulation software such as RADIANCE and DOE2 (see also subSection V.3.2.3 – Simulation). Based on the experience of my study, it will probably be necessary to create some new drawings because existing as-built drawings lack sufficient detail and accuracy to adequately describe the current situation (Figure 5.4.).

Past performance studies are also useful sources of information including: space utilization schedules, records (e.g., repairs, maintenance work, accidents, set points), historical and archived data. Electrical bills are particularly helpful for energy audits.

For my study, the protocol for document analysis is relatively straightforward. It includes the collection of as-built drawings from building managers (where available), a review of local codes and standards, and informal interviews with occupants and building managers. This information is used to generate a working set of functional design requirements (brief) for the situation being investigated. For example, for the HSL "individual lighting level," the basic set of functional requirement values collected in my study includes: occupant task, age, level of VDU use, and level of accuracy required. Document analysis is ideal for identifying values for higher level HSL requirements, such as climate, location, and applicable local building codes. (See also Appendix C – *WEDA Case Example*.)

A preliminary inspection of the spaces provides a general idea of the spaces involved and of occupant attitudes and common complaints. Done before any measurements are taken, this activity is very helpful for adjusting the "tools" to collect only needed data (i.e., information interesting or relevant to a particular workplace comfort issue).

V.3.2.2. Physical Monitoring and Measurement

In their paper on creating thermal comfort models based on field measurements, Gan and Croome (1994) argue models created based on laboratory testing do not accurately predict occupants' thermal responses in real workplaces, especially in naturally ventilated buildings. Varying cultural differences, adaptability, and expectations of the occupants are all thought to play a role in influencing perception of comfort (McIntyre, 1990). There is a role for field studies, therefore, in helping to create a more complete picture of what is actually going on in the indoor environment.

Arguably, physical field measures are considered by many researchers to be of little value in generating re-usable knowledge for other situations. The large number of inter-dependent variables found in real world cases make causal relationships harder to neatly isolate than in laboratory experiments. Another limitation is physical field measures are rarely comprehensive (include all rooms) or long-term (done over entire years or longer), and as a result provide only a "snap-shot" of current conditions at a particular time and place.

Despite these limitations, knowing what is actually happening in a room, even if it is only for a particular moment, can be very helpful if used in concert with other measures of performance. For example in confirming (or denying) the accuracy of other calculated or simulated predictions. Physical measurements can also provide us with a quantitative indication of what the user is talking about when they say they feel "hot" or "unsatisfied" if done at the same time as occupants are filling out questionnaires. Moreover, the increasing sophistication of building management systems [BMS] to monitor building services is making it possible to collect data about more rooms and over longer periods, as was demonstrated in a study by CBO-TNO and the University of Maastricht (Pernot & Zonneveldt, 2000) and (Kesteren & Meertens, 2000).

As part of developing a protocol for physical measures I observed the use of two field monitoring methods to determine whether or not long term monitoring would be practical for case data collection.

In the first study, long term monitoring (over several months) of lighting was done in two of the cellular case rooms selected for my study using the IEA TASK 21 protocol for the lighting measurement (Duffy, 1997; Velds & Christoffersen, 1998). In this approach sensors are set up in the room to measure at a minimum of three interior positions; in the daylighting zone, the mixed zone and the artificial light zone. The subdivision of the room into these various zones is based on a calculation of the *effective window height*. See also (Zonneveldt et al., 1998).

The location of the sensors in one of the case rooms (L) is shown in Figure 5.5.. Two sensors are placed at eye level on the walls, one on the back wall [A] and the other near the window [B]. Three additional sensors are placed on

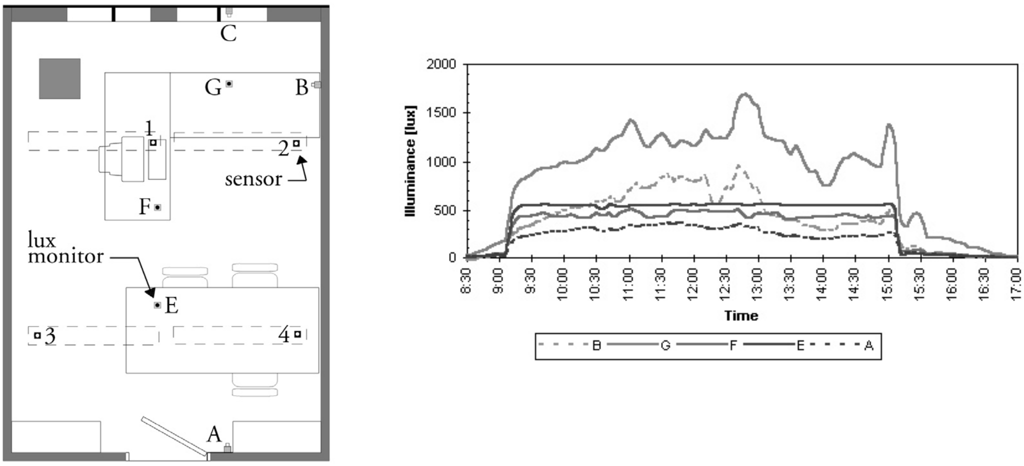


Figure 5.5. Location of Sensors in Case Room L and Lighting Levels Graph

the work surfaces: in the artificial light zone [E], mixed zone [F] and in the daylight zone [G] of the room. Exterior light levels are measured in both test rooms by a sensor placed vertically on the window [C]. Illuminance levels measured by all the sensors are sent to a computer data logger for recording and storage. In Case Room L, the ballast (power used) by each of the four sensor-controlled lamps was monitored. Collected data reveals the nature of energy use and range of task illuminance provided by daylight responsive lighting systems.

In the second study, short-term monitoring (one day) of various indoor environment parameters was done in a small government administration building using CBO-TNO's protocol for field measurement. In this approach a laboratory stand with measuring equipment attached to it is set up in the test area. Simple stand alone laptop computer-controlled loggers (e.g., Escort or Hanwell Humbug) attached to the various measuring instruments capture fluctuations in air temperature, relative humidity, air velocity and light levels over the course of a day (Figure 5.6.). Continuous measurements are complimented with spot measures of acoustic and ventilation system performance in suspected problem areas.

Based on my observations of long and short-term monitoring in the field, I concluded that taking physical measurements over long periods of time in real workplaces can be expensive and somewhat disruptive to the workers. Trading off what is likely a more accurate technique for one that an architect might actually do, I developed a collection method based on taking spot measures using small portable electronic devices. The protocol for undertaking spot measures, described in the following sub-section, is adapted from another field measurement method created by the CBO-TNO

Figure 5.6. CBO-TNO set-up for short-term continuous monitoring

SPOT MEASUREMENT PROTOCOL

The basic factors for determining physical environmental comfort used in my collection method are:

1. Air Temperature
2. Relative Humidity
3. Air Quality (Carbon Dioxide Level)
4. Lighting Levels (horizontal & vertical illuminance)
5. Air Flow
6. Acoustics (A-Weighted Sound Pressure Level)
7. (Digital) Photography, and
8. Outdoor Conditions.

The measuring devices used in my study are consistent with international and national standards (ISO 7726) (see Table 5.3.). Data collection sheets were created to make the recording of data easier and consistent. See also Appendix B – *Collection Tools*.

Table 5.3. Spot Measuring Devices

Measure	Device Used	Accuracy
Acoustics (A-weighted equivalent sound pressure level) [L_{eq} over 5 minutes] [1]	RION NA-27 Precision Integrating Sound Level Meter (alternate: Brüel & Kjaer Sound Level Meter 2219)	Calibrated on site (IEC ratings: 651:1979, 1-I and 804:1989, 1) ±1%
Light Level (vertical & horizontal) [LUX]	Hagner-5 Portable Universal Photometer	Calibrated on site (sensor is effected by local temperature). ±5%
Air Temperature [°C] & Relative Humidity [%RH]	Hygrotest 6400	
Air Flow (sketches & notes)	Dräger Rohrchen Air Current Tubes	Based on experience of evaluator.
CO_2 (parts per million)[2] [PPM]	Metrasonics AQ511	±3% of full scale at 25°C
Imagery [.jpg], or[.fpx]	Kodak DC210 Zoom Digital Camera, 28 mm lens	Highest resolution possible, appearance of room can be strongly influenced by the use of a flash
Additional Items Required: Measuring Tape, Tripod, Small Level (for levelling camera angle), Notebook, Data Collection Sheets		

[1] *Measurement of speech intelligibility is also a good indicator of disruptive noise in workplace settings.*
[2] *The results of indoor C02 measurements are used to specify minimum fresh air requirements (CIBSE, 1986). Poor air distribution in a space, however, can result in occupant dissatisfaction with the indoor air quality even if the ventilation rate is higher than the minimum requirement (Gan & Croome, 1994) p.782. Odor intensity is also an indicator of indoor air quality.*

To keep data collection as straightforward as possible, the choice of equipment and measures enable a single evaluator to carry out the investigation (Figure 5.7.).

For each work space, general conditions such as the date, time of day and observed outdoor weather (sunny, overcast, partly cloudy, and so on) are noted in the collection sheets. It is also desirable for factors such as heat and air exchange, to record additional outdoor weather conditions such as wind velocity, air temperature and humidity. It is not necessary to measure these latter conditions oneself. The simplest way to determine these values is to visit the Web site of a local meteorological station and download the information for the date of the test. An example of outdoor weather data collected for the workspaces is shown in Table 5.4..

Additional Physical Measures. The performance requirements for indoor climatic values can differ between standards. ISO 7726:1985 for example, recommends a slightly different approach than the one used in my study for determining thermal comfort. Where circumstances permit (or it

Table 5.4. Weather Conditions for POE on 18 March 1999

Time	Conditions	Temp [°C]	Wind Direction	Wind Speed	Visibility	Pressure
09:00	Lightly Cloudy	6.5	SSE	2 m/s	5000m	1027
11:00	Heavy Clouds	10.9	W	3 m/s	8000m	1023
13:00	Heavy Clouds	10.3	WSW	4 m/s	8000m	1022
15:00	Heavy Clouds	11.9	SSW	3 m/s	8000m	1019
17:00	Rain	9.0	WNW	4 m/s	2500m	1019
	MAX.	12.5				
	MIN.	2.1				

**Source: KNMI at* http://www.knmi.nl/voorl/weer/ *Some meteorological Web pages like this one show the conditions only for the current day. Data for other days, though available, may have to be purchased, so download the weather conditions on the day(s) of the physical measures.*

is warranted), the following additional physical measures may be useful as part of the POE (see Table 5.5.).

If this technique is used to evaluate an entire office building, measurements should be carried out on ground floor (or first floor in case no 'regular' office rooms are present on ground floor), top floor and a floor in between. On each floor, measurements should be carried out in rooms for each orientation and room type. Since my study was limited to workplaces located on single levels, this approach was not strictly followed.

Measurements need to be timed so conditions you want to study are represented. Both people and buildings are dynamic. Air quality measures are especially sensitive to time-of-day and exterior conditions. Depending on the way the building is operated, the concentration of contaminants tends to be higher during the morning. This is because ventilation rates and temperature regulation is relaxed in off-hours and ramped up before occupants arrive for work. Air quality is also seasonally affected where the mixture of exterior fresh air is reduced in winter to reduce heating costs.

Table 5.5. Additional Physical Measures

Measure	**Aspect**
Dust Particle indoor/outdoor ratio	Air Quality (Snijders, 2001)
Ventilation Rate [l/sec/m^2]	Air Quality / Thermal Comfort
Maximum Mean Air Velocity (v_a) [m/sec]	Thermal Comfort (heat by convection or loss by evaporation)

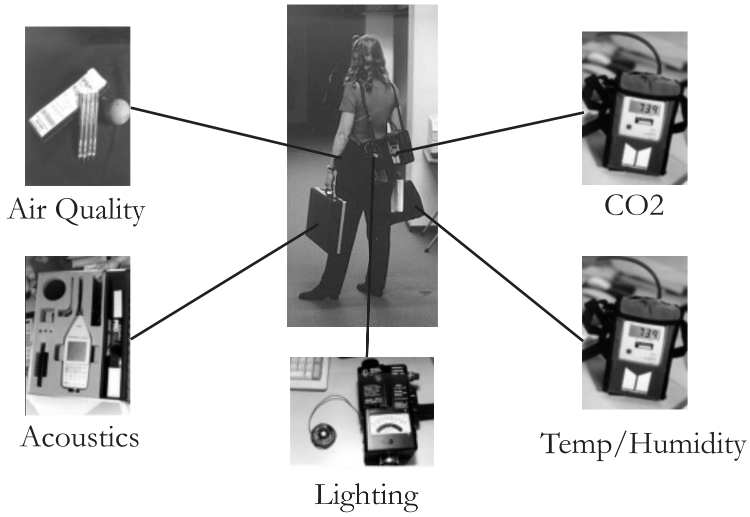


Figure 5.7. Evaluator and Measuring Devices

Aronoff and Kaplan (1995) suggest the following basic rules to follow for collecting field data: If you are looking for worst case scenario – pick a bad exterior climate day or when the office area has peak occupancy. If you are looking for an average day – collect data under less stringent conditions. In my study there is sample case data from both an "average day" and a "worst day." The cellular offices were all measured under average conditions, whereas the one workplace case was measured when the outdoor conditions were hotter than average.

Collection of physical data for all of the workspaces in my study took one investigator two days to complete. For one of the workplace studies, a two person measurement team was used so that all measurements could be completed in one day.

V.3.2.3. Simulation (Modelling & Calculations)

Modelling is a long-standing method for predicting the future performance of designs. For many designers this typically means building full size mock-ups or scale models of their designs in the laboratory or computer and observing how the design behaves under various simulated "real-life" conditions. In POE one has the advantage of being able to take measurements from a completed design, which is arguably a much more accurate way to capture building performance. As discussed in the previous sections, however, creating a complete picture of building performance based on physical field measurements is time-consuming, and requires a lot of experience and costly equipment.

An alternative to building scale models or undertaking field measurements is the use of complex algorithms or mathematical models. The use of complex algorithms is one of a number of accepted building performance assessment techniques described in (Loftness, Hartkopf, & Mill, 1989). The use of theoretical models in testing is also often referenced in code compliance evaluation, benchmarking, and international standards (i.e., ISO, AINSI, ASHRAE).

One of the most famous calculations used in the field of environmental engineering is one created by Fanger (1982). It is used for predicting indoor thermal comfort. Fanger's equation, based on laboratory experiments with human subjects, allows designers to calculate the comfort level indicators: PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) of occupants under various thermal conditions. Although at times controversial, Fanger's equation and the calculation of the PMV is becoming entrenched in building codes and standards as common measure of the thermal comfort in a space. Some design variables required for Fanger's equation, however, such as radiant temperature and air velocity (see Table 5.5.), are very difficult and expensive to accurately determine in field measurements. An alternative source for this information is through building design simulation.

Simulation is a valuable source of performance knowledge because it is difficult or overly expensive to manually predict the performance of certain indoor climate parameters with physical experiments or measurements (Hartog, Koutamanis, & Luscuere, 2000). Simulation can also offer advantages that evaluating a real design cannot. One advantage is the ability to see through scientific visualization phenomenon that cannot be normally seen. For example, the ability to see the pattern of air flowing through a room (Figure 5.8.). Another advantage is the ability to test a wide variety of effects over time such as examining a daylighting design during any time of year, day, or exterior weather conditions.

Faster and more powerful computers has increased the number of design tools capable of performing the very complex calculations necessary to simulate various indoor climate phenomena. To create simulations similar to that shown in the Figure 5.8., TNO-Bouw and others like (Hartog et al., 2000) and (Loomans, 1998), combine the use of Computational Fluid Dynamics [CFD] calculations and scientific visualization to predict and demonstrate airflow inside building spaces.

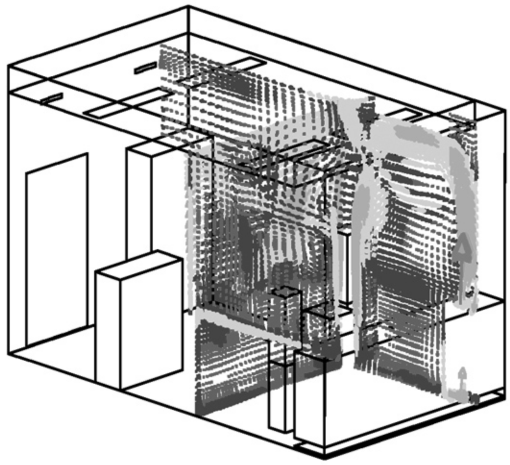


Figure 5.8. CFD simulation of Airflow (TNO-Bouw, 2003)

In another research, Hensen and Clarke (2000) describe the combined use of four simulation tools to predict the total annual energy performance for several alternate designs proposed for the renovation of a building in Glasgow. (Additional examples are at www.ipsa.org.) Their Performance Assessment Method [PAM] (Clarke et al., 1996) and (Hensen & Clarke, 2000) provides a good example of an integrated approach that is required to simulate combined building environmental effects. PAM takes advantage of the capabilities of tools such as the energy simulation program ESP-r. ESP-r is capable of covering energy and mass flows as well as the behaviour of multiple environmental control systems.

Such an integrated approach to using simulation tools was not employed in this particular study because such tools, if even available, are complex to learn and use. Comprehensive models of all of the office case rooms evaluated in my study would have taken a long time to input and calibrate. For my purposes, creating a method for the simulation of lighting comfort was sufficient to provide a sample of predicted (simulated) performance data for my prototype case-base.

SIMULATION PROTOCOL

To demonstrate how simulation might be used to show the environmental performance of an office case room, I applied a protocol developed by the CBO-TNO for using a suite of lighting simulation programs known collectively as RADIANCE. Radiance is a ray-tracing program created at the Lawrence Berkley National Laboratory that creates renderings as well quantifies the visual environment according to measures such as daylight factors, directional transmittance and illuminance vectors (Ward, 1993) and (LBNL, 1997).

The steps for creating the simulation are:

1) create the computer model
2) run the simulation
3) express the results according to various measures
4) analyze the simulation results

Create the computer model. To create a post-occupancy simulation of an office test room in Radiance requires inputting material properties and 3D geometric measurements of the room and its furnishings, and descriptions of light sources, including lighting fixtures and windows (Table 5.6.). Rendering the image itself requires the additional specification of the desired view point, direction and angle.

Much of the information used to create the model can be taken from the design or design documentation. *Generators* and libraries provide additional support for model creation. Generators are programs associated with Radiance used to help produce scene description files. For example, Gensky produces sun and sky conditions corresponding to a given time and date. Small libraries of materials, objects and luminaire data are also available. Entering geometric information directly into Radiance involves a particularly arduous process of encoding object coordinates. Fortunately, a translator for AutoCAD's DXF format provides an opportunity to import an existing or new 3D geometric model from a more intuitive and easy to use CAD environment.

Despite the existence of these various auxiliary aids to model creation described above, it is my experience that model creation in Radiance is very difficult. As with any simulation, the creation of an accurate model is critical to getting accurate results ("garbage in, garbage out"). In this project, the assistance of someone with expertise in the program and lighting theory was absolutely critical.

Figure 5.9. Simulation (left) and Photograph (right) of Lighting Conditions

Table 5.6. Computer Model of Case

Inputs
Material Properties (i.e., for floor, ceiling, walls, furnishings): -Reflectance Factor -Transmission -Colour Room and Furniture Surface Dimensions in 3D Luminance Distribution Luminaire Characteristics[1] Glazing Transmission Shading Device Data[2] Climatic Data[3]

[1]*Luminaire information is drawn from a database supplied by the manufacturer. For pendants and uplighters the position of the luminaire needs to be inputted so it can be located in 3D space.*
[2]*A utility attached to RADIANCE creates a simulation of the effects of venetian blinds when provided the curvature, width and angle information.*
[3]*CIE Overcast sky model was used for the simulation in my study.*

Run the simulation. Radiance uses a ray-tracing calculation method that follows light from light emitters and works outwards. The amount of calculation necessary to produce the rendering is highly influenced by the number of light sources in the scene and the complexity of the scene (i.e., sources of reflected and indirect light). The generation of a fully detailed and high resolution rendering of an office space in Radiance is time-consuming. To create the single rendering of Case Room L, with daylight entering through venetian blinds and indirect pendant lighting, (shown in Figure 5.9.) took over 5 hours to create.

To save time, it may be helpful to use generic office room simulations. In my study, generic simulated images were also used to represent simulated daylighting conditions in some of the cases. These are selected from a database of pre-rendered examples developed by CBO-TNO (2002).

The use of generic renderings means some information about the actual office test room are not shown. When supporting conceptual design decision-making, however, a lot of detailed information is often unnecessary. Too much information may obscure an important message the simulated scene is trying to communicate. CBO's models, for example, only simulate daylighting and not electrical lighting or furnishing effects. Daylighting performance, unlike electrical lighting, is drastically effected by early design decisions such as siting and orientation of the building. During conceptual design, designers trying to maximize future energy savings should concentrate on taking advantage of the contribution of light from natural sources first before considering the design of the electrical lighting.

Express the results. Eight computer-generated images of the lighting performance are included for each of my office environment test rooms:

1) Room Perspective Rendering
2) Cross Section Rendering
3) Plan Rendering
4) Side Wall Rendering
5) Rear Wall Rendering
6) Daylight Factor Distribution Plan
7) Daylight Factor Distribution Section
8) False Colour Image

These images were selected because they provide a good coverage of the lighting performance from various angles around the office test room.

Analyze the simulation results. The renderings placed alongside the photographic images of the office test room (Figure 5.9.) demonstrate how accurately simulation matches with the real design performance (an indication of the quality of the original lighting model). The Radiance simulations of the lighting of my test rooms are very good at showing potential sources of glare (illuminance levels), the contribution of light from daylighting (daylight factors), and the appearance of the room under various lighting conditions (qualitative effect). Providing unique, semi-quantified views of the world, such as the false colour image, is one of the advantages of simulation over other performance assessment methods. The false colour image of illuminance values on room surfaces quickly tells the viewer where levels may be exceeding acceptable thresholds (Figure 5.10.).

Unfortunately, Radiance simulations are incapable of communicating the secondary environmental effects of a lighting design. For example, during the afternoon high heat gains are known to occur in the office test rooms because of the large, west-facing windows. This effect creates uncomfortable conditions for the occupants and high cooling loads in summer. I found these aspects of performance, however, were picked up through the use of the other tools in the toolkit such as, occupant surveys and physical spot measures.

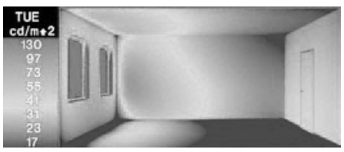


Figure 5.10. False colour image of Case Room

V.3.2.4. Observation Study

Another useful dimension of building performance assessment identified in domain literature is *expert/informed judgement* (Loftness et al., 1989). While occupants are better at identifying particular comfort problems in their workplace environment, experts are better equipped to identify the potential cause of (and solution for) that discomfort. This is partly because occupants are themselves part of the workplace environment. That is, the performance of the work environment is a result of the interrelationship between the occupant and the building systems. Occupants can have a direct effect on the performance environment systems through building controls or make-shift modifications. Occupants can also, however, adapt their own behaviour and clothing to make themselves comfortable when building environmental systems are performing poorly. Occupants may be unaware they are being effected by their environment even though they are exhibiting obvious stress behaviours such as taking frequent breaks away from the office.

The function of an observation study is to have experts formally survey and judge the physical (visible) and sensory (invisible stimuli) features of the workspace environment. According to Smith and Kearny (1994) such a procedure is done to:

- confirm the existing (as-built) physical features (fixed),
- establish the location of furnishings and equipment (changeable),
- identify current sensory features of the environment, and
- identify current problems (and potential solutions).

OBSERVATION PROTOCOL

The workplace observation assessment methodology used in my study is an adaptation of three different methods. These methods are: (1) the workspace features survey of (Smith & Kearny, 1994), (2) the building systems assessment method of (TNO-Bouw, 1992) and (3) the time-use survey from a lighting control study by (LRC/NCAR 1996:47-60). All of these methods involve experts, walkthroughs of the workplace and completion of survey worksheets (see POE tools in Appendix B).

The observation procedure is divided into three parts, each with a corresponding worksheet:

Part A – Design Validation
Part B – Design Features
Part C – Workspace Observation Log

Since the procedure involves several parts, it requires multiple visits to the areas being observed. Each time the expert observer visits a workplace s/he must work as unobtrusively as possible and avoid engaging in conversation with the occupants.

Before beginning the observation study it is important to obtain an as-built floor plan of the areas being observed. Worksheet Part A (see Appendix B) is used to validate the floor plan for accuracy. When existing floor plans are either unavailable or too difficult to obtain, as was the case with my test rooms, new floor plans need to be prepared from scratch. Although potentially time-consuming to obtain or prepare, floor plans are necessary for note-taking, communication and for use with other POE tools (e.g., simulation).

A. Design Validation. Design validation is a procedure to establish the current physical features of the workplace including the types of building service systems solutions used. Using the worksheet, the expert relates each environmental service system (general setting, lighting HVAC, Controls, and Acoustics) to a typological model. These models, drawn from domain literature, define the actual systems in terms of the relevant component variables that influence the performance of an office environment system. For lighting, a typological model from the work of de Groot (1999) is used. This model contains multiple performance variables for daylighting, control, and electrical lighting. For example, the six key variables for electrical lighting designs are: illuminance (pre)setting, light direction, distribution, luminaire type and position. An excerpt from collection sheet is shown in Figure 5.11. Relating each building system to a model helps to save time by eliminating the collection of unnecessary details. It also helps to categorize the information about the building services stored for each office room case for easier recall when later searching the case-base.

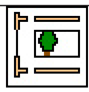
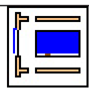
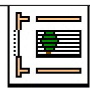
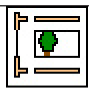
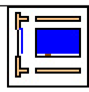
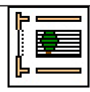
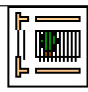
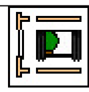
	Control Outside (Section / elevation)	 none	 roller	 venetian		
	Control Inside (Section / elevation)	 none	 roller	 venetian	 vertical	 drape

Figure 5.11. Excerpt from Worksheet Part A identifying elements of Daylight Control

B. Design Features. The purpose of the design features survey is to first identify the physical (visible) and sensory (invisible stimuli) features of the workplace and second, relate these to the needs of the occupants (Smith et al., 1994). For this stage is important that observations are planned for a time when the occupants are present.

Working with a current floor plan and a worksheet, the observer starts by identifying what physical aspects of the workplace are fixed (e.g., a ventilation shaft) and which are changeable (e.g., furnishings and equipment). The observer then notes the sensory features (e.g., strong lighting, exterior noise, odours…etc.) of the workplace, noting potential problems and opportunities.

Next, instead of concentrating on design features, the expert watches the people in the workplace environment, looking for signs of the workplace environment interfering in occupant work performance. This includes noting any stress behaviours or modifications made by occupants to cope with poor environmental conditions such as blocking air supply vents with cardboard or the using improvised glare shields on computer screens. Where appropriate, photography is used to enhance the survey. For example, a photograph taken during the observational study of Workplace P (Figure 5.12.), shows how occupants keep the blinds on large windows constantly shut during the day to reduce glare.

C. Observation Log. A workplace observation log is completed to understand the use of the workspace over an extended period of time. This information is helpful because it provides a picture of the demands placed on the building services systems over time. Like the Time Utilization Studies [TUS] by (Duffy, 1997) it answers such questions about work patterns such as, When is the area used? Is it constantly occupied or is it mostly empty? What tasks are being done (tasks that are sensitive or insensitive to environmental interference)? Unlike TUS, however, my method captures more than work pattern information. It also seeks to determine a pattern of building systems use by keeping track of how occupants interact with the building service systems controls (e.g., thermostats and blinds). Controls allow occupants to manage their own performance by influencing their work environment; their lighting, heating/cooling, ventilation and so on.

In my study observations were logged hourly during a "typical" day, including one hour before and one hour after regular working hours (11 observations in total). This was done because several of the subjects in my study work outside of normal working hours when, as in many office buildings, the HVAC system is turned off.

Analysis. The key results of Part A, the design validation stage, is a description of the physical properties of the building services system design and an accurate floor plan. The outcome of Part B, the design features stage, is the identification of areas of workplace interference and the reaction of occupants to this interference. Analysis of Part C, the observation log, shows how a given space is used over a period of time.

It is interesting to check for similarities and differences between the outcomes of the observation study with the data collected using other POE tools. In particular, to compare the occupant's experience, as reported in the questionnaires, with the expert's observations. Through such comparisons, the observed results augment and aid analysis of the perceived (qualitative) and measured (quantitative) values.

V.3.2.5. Occupant Surveys & Interviews

The main reason for being concerned at all about the quality of building environment systems is to make sure that people are comfortable and able to do their work tasks. The easiest way to find out if an occupant is uncomfortable or unable to perform their work task because of poor environmental conditions is to ask them.

One of the advantages of talking to occupants is that they are likely to have had the most long-term experience with the environments being tested. They also know what performance issues are most important to them.

Some argue the value of occupant opinions is limited, since these can be easily influenced by factors that have nothing to do at all with building services, such as an employee's dissatisfaction with their boss. Adrian Leaman (1997) states that building services designers tend, however, to rely heavily on physiological data derived in the laboratory, missing out on the more subtle behavioural and attitudinal aspects of building use:

> "In addition to the possibility that the inferences drawn from physiological data may be flawed because they are based on controlled experiments rather than real events, building designers need much more information on human interaction with buildings and their services if they are to provide systems which support comfortable, satisfied and productive people." (Ibid. p.37)

The best way to obtain this information, according to Leaman (1997), is through behavioural studies of building occupants (see previous sub-Section V.3.2.4. *Observation study*), and the use of self-completion questionnaires

Figure 5.12. Occupant's modification in Workplace P

covering key environmental issues (ibid.). Smith and Kearny (1994), argue that interviews should take a leading role in the collection of human-building interaction data. They suggest distribution of self-completion surveys to individuals should be carried out only after it is determined to be necessary by group and individual interviews. A good technique for structured interviews (following a prescribed list of questions) is described in (Smith et al., 1994).

In my study, because the number of occupants involved was so small, it was unnecessary to do structured interviews. Informal, unstructured interviews with building managers and occupants were good enough to help identify some of the potential problem areas and attitudes about the workplace. I concentrated on designing a self-completion questionnaire that could be filled out by workplace occupants near or at the same time that I took physical spot measurements.

Occupant Survey

The goal of occupant interviews and self-completion questionnaires is to determine what the occupants perceive is the environmental performance of their workspace. The objective for my questionnaire is to capture occupant attitudes, as well as identify what is working well and what is problematic about their workplace environmental systems. Since no existing questionnaire was available to collect this particular data, one needed to be created.

During pre-testing of the POE tools occupants were asked to fill in four different occupant questionnaires:

- Usable Tools (Preiser, Rabinowitz, & White, 1988b)
- Workplace Performance Analysis (DEGW Twijnstra Gudde, 1997)
- Building Survey (Building Use Studies Ltd., 1997), and
- IEA Task 21 Lighting Conditions Survey (Hygge & Lofberg, 1996) (Atif, Love, & Littlefair, 1997)

The first two questionnaires are general, *workplace performance surveys* (Duffy, 1997) and do not particularly focus on environmental comfort. They mainly deal with what Preiser, Rabinowitz and White (1988a) refer to as:

> "Functional appropriateness (adequacy of space, health, safety, and security issues, for example and behavioural or psychological concerns such as the "image" of the facility." p.55

The Building Use Studies' "Building Survey" considers more environmental issues. IEA's questionnaire focuses on worker's concerns regarding lighting.

Following the pre-testing, feedback collected from the participants was used to create a single (hybrid) occupant survey questionnaire. This hybrid occupant survey contains the "best of" from the various surveys described above. The new survey was used to collect data from all of the workspace cases. A copy of the final version of the occupant survey questionnaire can be found in Appendix B.

Survey design. In keeping with my purpose, my occupant survey emphasizes collecting information about work patterns and environmental comfort (i.e., lighting, acoustics, thermal comfort and air quality). The questionnaire is divided into seven modules (personal information, task description, thermal, lighting, air quality, acoustics, and general performance). The specific criteria used to determine perceived environmental comfort are described in Table 5.1..

On the questionnaire there are three main types of questions:

1) Facts (information about the occupants)
2) Behaviour (what they do), and
3) Attitude (what they think about the environment they work in)

Facts (e.g., age, sex) are collected using specific questions to help set respondents into particular groups identified by other researchers to be significant to indoor environment study. For example, persons over 40 are considered to need higher lighting levels than younger persons (IESNA, 1993).

Behaviour questions in the questionnaire are used to collect a description of the respondent's work activities and use of their office space, as well as how they respond to unfavourable environmental conditions (for example: close the blinds, call building services). The questions about work activities are based on work pattern model by (Duffy, 1997)). This was done to help make a correlation between office environments and workpattern types.

The last, but most important aspect of the questionnaire is related to collecting occupant's attitude towards the indoor environment. According to (Robson, 1993), beliefs and attitudes are difficult to get at because they are so complex and can be easily influenced by question wording and sequence (p. 228). Therefore, special attention was paid to the design of the questions in the questionnaire.

To determine how occupants felt about their environment, a *semantic differential scale* (Osgood et al., 1957 in (Robson 1993)) is used. Participants are asked to respond to questions related to a bipolar rating scale (Figure 5.13.).

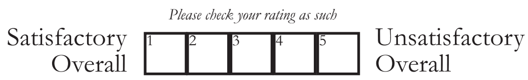


Figure 5.13. Bipolar Rating Scale from Occupant Survey

An uneven number is used to divide the scale to allow for a "neutral" response. This is done because "for many environmental features, a neutral rating is actually a good indicator and a desirable score," (Aronoff & Kaplan, 1995) p. 348. A good work environment is unobtrusive and "invisible" to the occupant. Occupants generally are unaware of their work settings unless something negative or annoying is happening. If occupants do have a positive response to a building environment it may indicate a good system, but it might also be indicative of a system that is over-performing or is especially important to the users.

Another aspect of semantic scales that is debated by data collectors is how many divisions to use. Occupant surveys that were reviewed as part of my study contained rating scales ranging anywhere from three to eleven points. In the end, it was decided to use a five point ordinal rating scale for most of the questions. Although smaller scales limit the degrees of choice and therefore, precision (e.g., finer distinction between levels of satisfaction, control and so on), a five point scale provides enough data for analysis and is easier to understand than larger scales. Aronoff and Kaplan (1995) report "...subtle shades of meaning offered by the larger scales are interpreted inconsistently by respondents, increasing the level of random error in the data" (p. 347). In addition to rating the indoor environment, the questionnaire in my study also asks occupants to indicate importance of each issue to their work tasks and the effect of the environment on their productivity.

Although open questions are generally avoided because they are hard to code and analyze, in my survey, space is provided for respondents to make additional remarks or *stories*. Stories are useful for capturing issues or interesting aspects about the workplace environment that were unanticipated in the original survey question design.

Timing. While self-completion questionnaires are generally ineffective for identifying the cause of building servicing problems, they can provide a starting point for focusing a physical investigation later on. For this reason, occupant surveys and interviews are usually done first, before any physical measures are taken. In my study, however, the distribution of the occupant surveys was timed to be *simultaneous* with the taking of the physical spot measures. This was done in case some correlation might later be made between perceived and measured values (e.g., occupant's reported "hot" office was measured to be 28°C).

With a limited number of participants, it was possible for the evaluator to distribute the surveys to each individual, code the data by hand and then enter it into the computer (i.e., into a Excel™ spreadsheet) for analysis. For a larger survey, a better approach would be to use computer-based survey forms distributed via the internet, as was done by (Finch, 1999) during a POE of a large office building in the UK. This allows the participant to enter their data directly into the computer for analysis.

Analysis. The key results of the occupant survey are to determine if occupants feel that aspects of their work environment are making them uncomfortable to the point that they are unable to perform their work tasks effectively. This is done both specifically and generally in the questionnaire. In sections dealing with a particular environmental building system (such as lighting) occupants are asked how *satisfied overall* they are and how *important* that system is to their work task(s). Obviously, when an occupant is very unsatisfied with a building system that is critical to their work task it can be a potentially serious problem. Occupants were also asked general questions such as if their environment was meeting their needs, and to estimate the impact of their working environment on their overall productivity.

In terms of evaluating workplace comfort, I found measuring occupant's opinions should be given a very high priority (see also Case Study 1 – Section V.4). Like Boyce and Eklund (1995), I have tried to deal with the subjective nature of people's opinions in evaluation by using *converging operations*.

Converging operations is an approach to measuring a single phenomenon in several different ways. Cases evaluated with my toolkit were measured in four ways (i.e. Measured-Observed-Perceived-Simulated approaches) and the results are compared with each other. If the different approaches converge to the same conclusion, the conclusion is more likely to be sound. If they do not, the conclusion is more likely to be unsound.

V.4. Case Studies

The previous section describes the development of and procedures for using the various tools assembled to create my POE toolkit. This section briefly summarizes the four workplace environment pilot studies that were carried out using the POE toolkit and highlight some of the findings. Afterwards, Section V.5. explains the conceptual data models used to organize and ultimately represent collected case data in a computer.

Case study 1 was undertaken on the 10th level of a 40 year old University building located in the Netherlands. The area covered by the POE includes four cellular offices occupied by a building research group (Figure 5.14.). Each room contained one or two occupants with mainly desk-based work tasks (i.e., using the telephone, writing, or working on the computer). The office rooms are very similar to each other in orientation, size, and layout. This type of cellular office rooms is typical of the kind of fit-out and space planning found in many offices in the Netherlands. What made these offices interesting was that each had been retrofitted with a unique innovative lighting system (summarized in Table 5.7.).

Innovative servicing systems strive to provide features that enhance flexibility, manageability, and efficiency over traditional systems. The main business driver for these innovative lighting design systems was to provide higher energy efficiency.

Evaluations in these areas were carried out at various stages of the development of the toolkit. The evaluation using the toolkit showed that all of the lighting installations performed better than average in terms of energy efficiency. There was a profound difference, however, in terms of whether people considered their rooms comfortable.

Probably the most significant realization about how important qualitative measures are (perceived and observed outcomes), came from the experience of using my toolkit to collect data about Case Room C. Case Room C contained a very innovative indirect lighting system and a mirrored ceiling to help reflect daylight to the back of the room. A motorized venetian sun

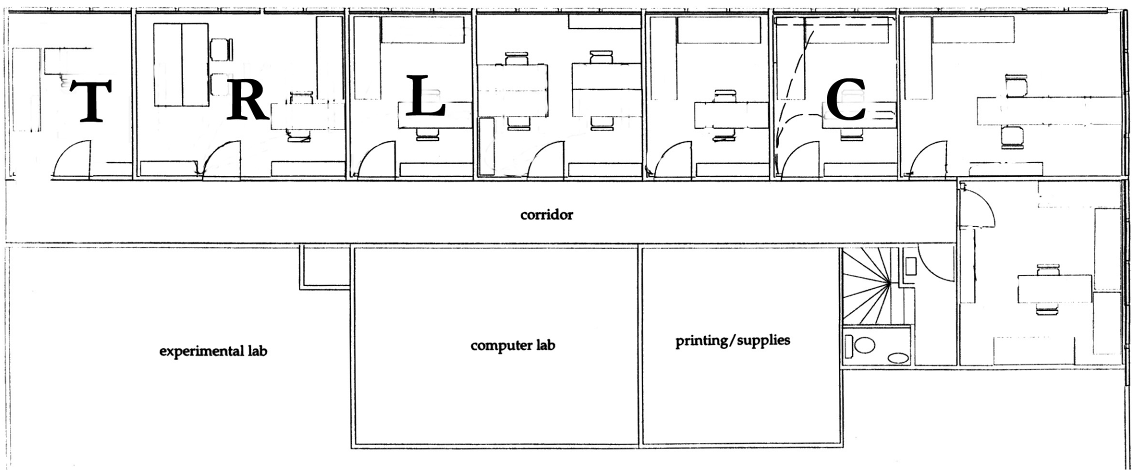


Figure 5.14. Floor plan showing location of Cases T, R, L, C

blind on the window ensures the convex mirrored slats were automatically kept at a perfect angle to maximize daylight reflection into the room (see Figure 5.15.).

Physical measurements (long term monitoring and spot measures) in Case Room C revealed the lighting system design was highly effective. Lighting levels across the room were even and task illuminances were within the required design ranges of 300 lux. During the daytime, daylight penetrated all the way to the back of the room, thereby saving energy by reducing the need for electric lighting. Despite this, even before the experimental period was over, the occupant asked for the lighting system to be removed from his room. Why?

The reason became evident in the occupant's responses in the questionnaire. The occupant described his room as uncomfortably dim, "dark" and "dingy." The mirrored ceiling provided a constant source of distraction as people and cars constantly moving on the street outside would be reflected upside down overhead. The intermittent operation of the venetian blind motor was noisy and distracting. The observation study further confirmed the poor comfort performance of the design. Modifications by the occupant (unplugging the motor) and stress behaviours, such as finding other locations in the workplace to perform normal work tasks, all suggested an uncomfortable work environment.

Case Study 1 revealed it is important to study a particular phenomenon in several different ways and the general primacy of occupant opinions. Although the predicted and physical outcomes for Case Room C were within acceptable limits, the perceived and observed outcomes were needed to provide a full picture of the workspace performance. If an architect

Table 5.7. Summary of Case Study 1

		Attributes Collected			
	Lighting System Solution	**M**	**O**	**P**	**S**
 **Case L**	**Indirect/direct combination lighting system**. Energy efficient T5 flourescent tube lighting. Four pendant direct-indirect luminaries. Standard white mini-venetian blinds have separate adjustment of top and bottom halves to maximize daylight penetration. Light sensors in each luminaire pointed at work surface automatically adjust output to a design level of 500 lux.	●	●	●	●
 **Case C**	**Indirect lighting system.** Energy efficient T5 fluorescent tube lighting. Two uplighting luminaries at window two in-ceiling luminaries at back wall. Reflective exterior-facing upper portion of horizontal mini-venetian blinds with concave profile to "scoop". Slat angle is adjusted automatically to maximize daylight penetration by an electric motor. Reflective ceiling at window side. Single sensor at rear of room dim electric lighting to maintain a design level of 300 lux on the work surface.	●	●	●	●
 **Case** T	**Indirect lighting system.**T5 fluorescent tube lighting. One pendant luminaire over work surface. Standard (50mm) horizontal blinds. Sensor pointing downwards to work surface automatically adjusts output to 300 lux.	●	❍	●	❍
 **Case** R	**Direct lighting system.** T5 fluorescent tube lighting. Four in-ceiling luminaries. Output adjustable in four steps with hand-held remote control. Occupancy sensor system turns lighting off after 10 if room is not being used	●	❍	●	❍

❍ = partial collection

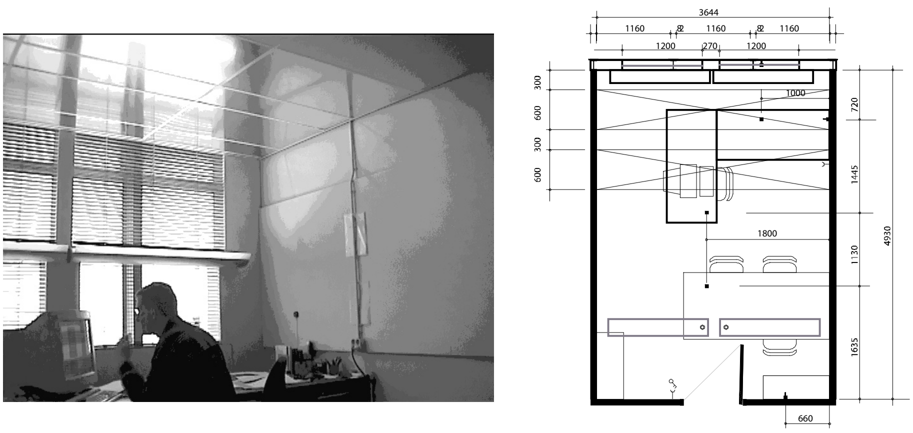


Figure 5.15. Case Room C

were to choose this solution based on energy-efficiency alone without considering the comfort of the occupant they may make a serious error. Afterall, what good would energy-saving workspace be if no one will work in it? Cases need to contain both quantitative with qualitative criteria to allow for checking of congruence or incongruence across multiple dimensions.

Case study 2 was undertaken in a 1999 addition to the ground floor of the same University building of Case study 1. It is occupied by the University Administration. The area covered by the POE included two cellular offices; a large executive office and adjacent secretarial office area. The lighting in both areas consists of round downlights with energy efficient compact fluorescent lamps.

Figure 5.16. Case Study 2 - Office H (left) and Glare on Computer Screen in Office S (right)

The evaluation of the toolkit showed executive Office H performed as well or better than average in terms of comfort across all measures Privacy, fresh air (openable windows), and room size were all cited by the occupant as having the most positive impact on their ability to work. Occupants in Office S reported productivity improvements up to 10% higher in comparison to their former workspace and were also very satisfied with their environmental conditions. Physical measurements revealed significant problems with glare, however, particularly on VDU screens (Figure 5.16). Although the occupants use their computers very little to do their job (10-15% of time per week), this could still pose a problem that will become more evident in the long term. Remediation, in the form of sun blinds at the window, or re-orientation of the screens will likely be necessary.

Case study 3 was undertaken in a historic warehouse building located in London, England. The building is owned and occupied by a large architectural company. The area covered by the survey, shown in Figure 5.17, is a *flexible style* workplace introduced into the first level of the building in 1997. Some adjustments were made to accent and task lighting, but for the most part building services strategies (in particular, the air-conditioning system) were generally unchanged. Physical measurements were made in a *hive*, *den*, *cell, hub* and two *group* workspaces. Some observational data was collected. The balance of case data was assembled from other sources, including two POE studies of the workplace done by other researchers.

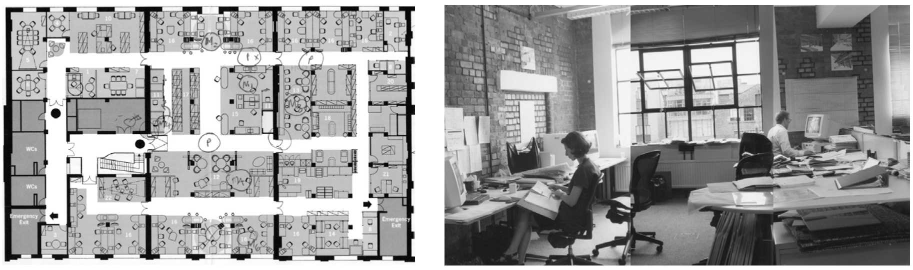


Figure 5.17. Case Study 3 Plan and Group Room Photograph (5 occupants)

The main business driver for flexible style workplaces is a higher accommodation level (the adjustment of mobile/private space and resource use allows for up to 25-30% increase in accommodation over conventional offices). As this is a relatively new concept for workplace design, less is known about which environmental services work best with it. Some initial research is described in (Laing, Duffy, Jaunzens, & Willis, 1998).

Despite a relatively large building depth, cooling is provided in this workplace by a simple cross ventilation system; openable windows with a central duct down the center that provides "a little forced ventilation" (Sims, 1998). According to the designer, the service systems were considered to be adequate because the workplace is not a "static working environment," but flexible and dynamic (ibid.).

The two days of the POE evaluation were some of the hottest ever recorded for London, with outside temperatures soaring over 36°C. The evaluation showed, under these extreme conditions the HVAC system was worse than average in providing human thermal comfort (average air temperature 26.6°C, relative humidity 39.96%). Where temperature and relative humidity levels were more comfortable, near the periphery and openable windows, glare became a problem, particularly in the group areas on the west side. Lighting levels were quite low (task illuminance under 200 lux) in central areas. This is likely because much of the electric lighting had been turned off to reduce heat gain. Acoustic levels were also high throughout, with recorded levels ranging between 58-60 DBA.

Case study 4 was undertaken in the Head Office building of a large multinational company located in Eindhoven. The building was built in the 1960s. The area covered by the evaluation is a *flexible-style workplace* introduced on the fifth floor in 1998. A new energy-efficient lighting system was installed, but the area is still serviced by the existing building HVAC system. Physical measurements were made in a *hive*, *den*, *group,* and *cell* ("cocoon") work space within the workplace (Figure 5.18). Observational data was also collected. The balance of case data was assembled from other sources including a journal article (ILR, 1998) and a occupant survey by (Tenner, 1998).

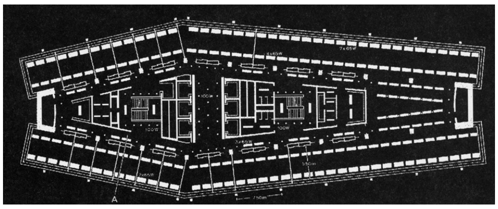


Figure 5.18. Case Study 4 Original Plan (left) and New "Cocoon" and Meeting Area (right) (ILR, 1998).

Like Case study 3, the main business driver for the workplace design in Case study 4 is the ability to increase accommodation levels. The building in Case Study 4, however, also had to meet stricter building regulations of the Netherlands regarding worker safety and comfort as well as energy efficiency.

The evaluation carried out using the physical measurement tools showed this work environment performed as well or better than average in terms of environmental comfort. There was some incongruence with this conclusion, however, with the observational and perceived data. According to the occupants, lack of privacy, sound from colleagues, and poor exterior view were problems (ibid.). The perception of lack of privacy may be a result of occupants used to cellular offices needing to "get used to" the non-traditional open style plan of the new office. The tolerance for a lower level acoustical privacy may also be due to this, as field measurements did not record unusually high levels of noise. Most areas measured around 40 DBA. The highest level of 50 DBA was measured at the secretarial area (hive) which is located adjacent to the elevators, which is indeed an area of high traffic and conversation. The lack of an exterior view was a problem, but perhaps a temporary one. Occupants along the east periphery would close the large vertical blinds in the morning to keep out the sun, and they would remain closed throughout the day. As a result, those farther away from the windows complained of having no external view and control. Facility managers, however, were in the process of considering changing the window coverings (i.e., to horizontal and/or automatically adjusted) which will likely solve the problem.

Lessons Learned. The four case studies described above demonstrate the utility of the POE toolkit to easily and inexpensively collect interesting information to create cases about workplace comfort. Sometimes, as in Case studies 2 and 3, it is possible to assemble case data from other sources which offers a further time and cost savings. As explained in Case study 1, however, it is very important to evaluate case performance in terms of all of the four MOPS perspectives – Measured (physical measures), Observed (experts' opinions), Perceived (user opinions) and Simulated (modelled or calculated performance) to get a complete picture of performance.

V.5. Representing Case Data in a CBR system [CDM]

At the end of this phase of the study I had collected information related to all of the components of a workplace case identified in the knoweldge model. It was time to create a case-base. This sub-Section discusses the conceptual model used to organize case information so it could be represented and stored in a computer.

Organization. A Conceptual Data Model [CDM] is a diagrammatic way of representing the structure of data stored in a computer database. The CDM for cases implemented in WEDA consists of attributes that were collected using the POE toolkit. The organization of the attributes is based on the building performance evaluation domain model (see Chapter II). At the top level of the data model, there are attributes to describe each case at each Architectural System Level [ASL]: *site*, *building*, *floor level* (workplace), and *workspace* (Figure 5.19.).

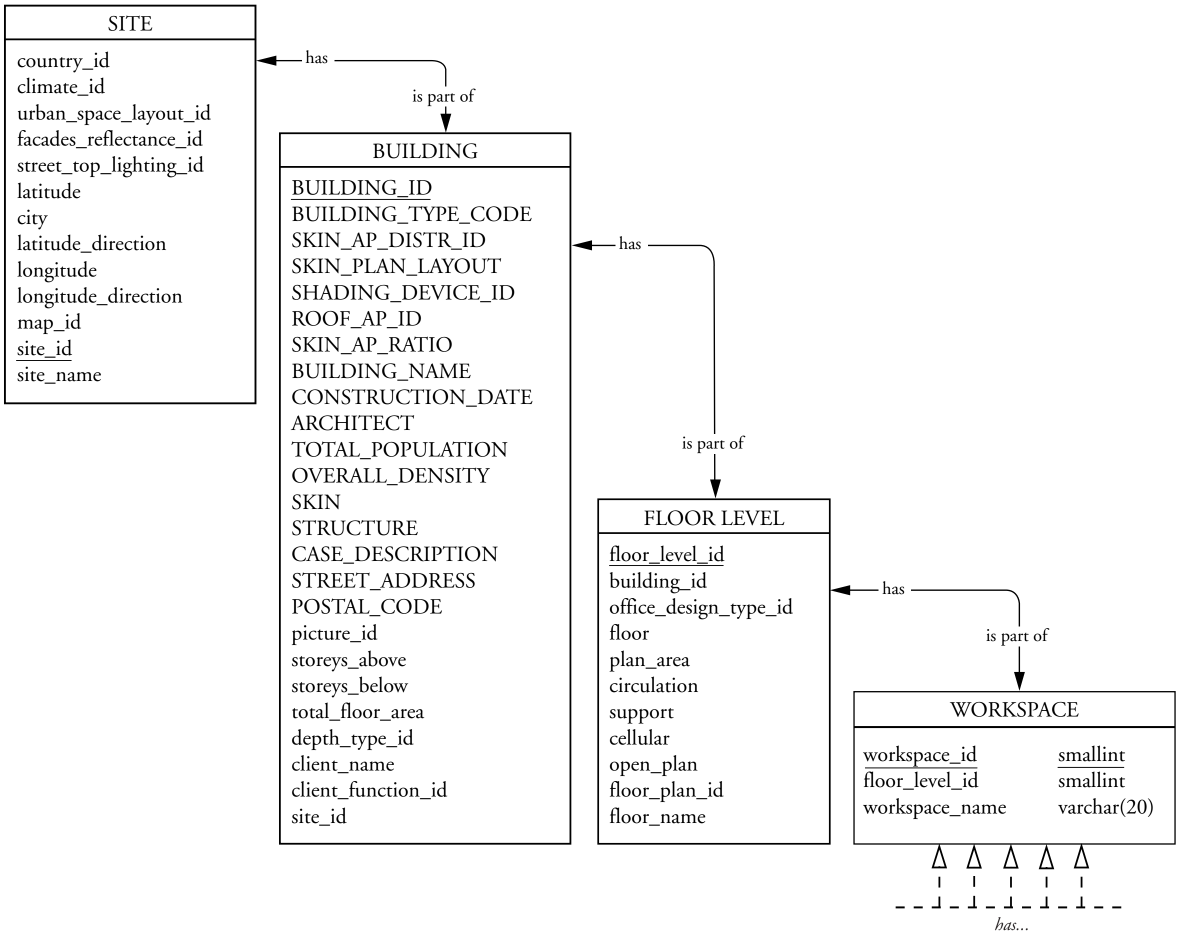


Figure 5.19. Conceptual Data Model for WEDA ASL Attributes

At the top level of the workspace CDM for the cellular office cases, attributes are further divided among one of three categories (Figure 5.20) (see also Section V.2. – *Case Components*):

1) Brief
2) Solution
3) Outcome

The *brief* attributes describe the key functional requirements for the workspace environment and its occupants. The *solution* attributes describe the key elements of the environmental systems used in the cases; mostly relating to lighting systems. In the Model *outcome* attributes are further divided into one of for sub-categories:

3.1) Measured
3.2) Observed
3.3) Perceived
3.4) Simulated

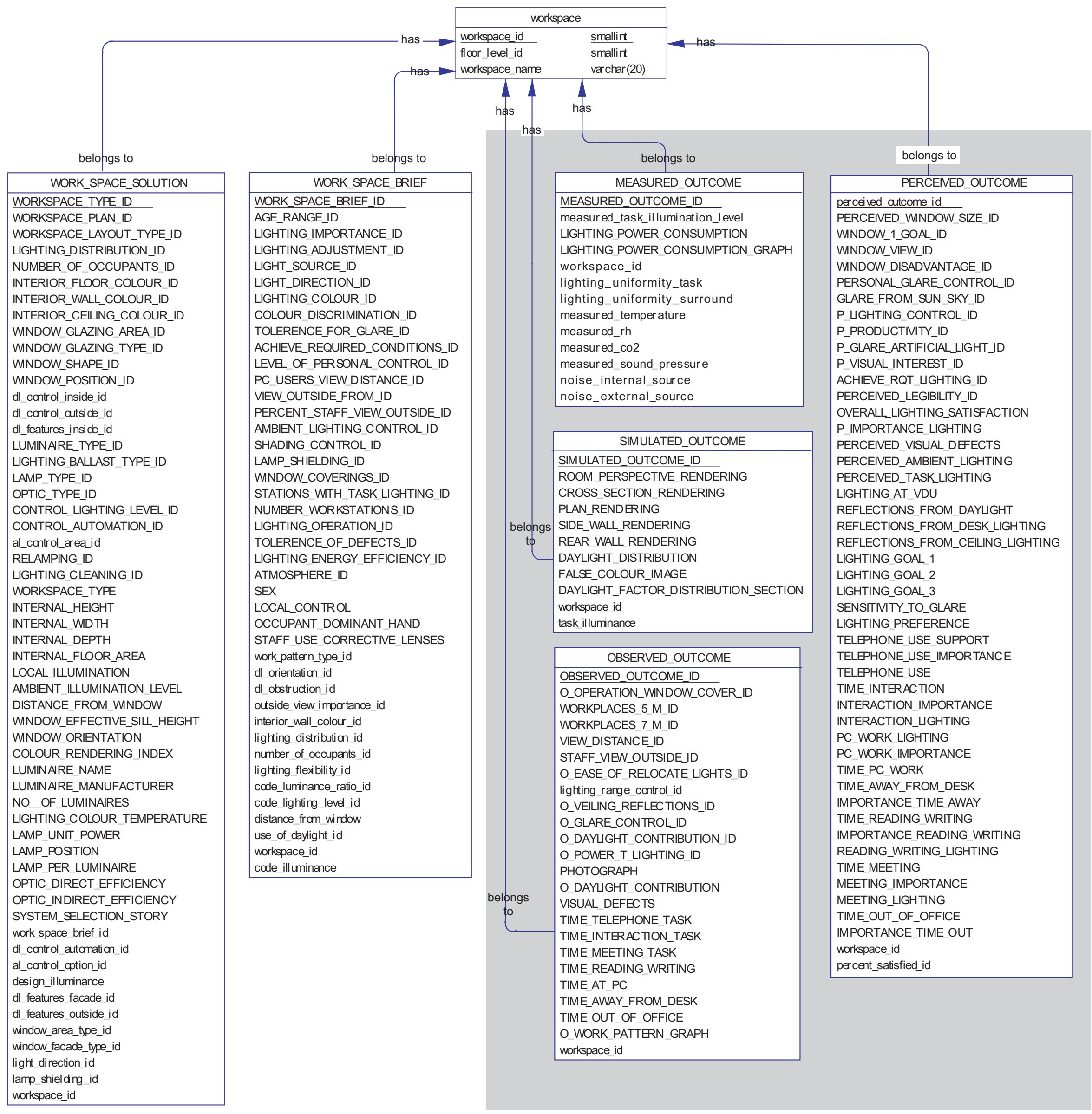


Figure 5.20. Workspace Conceptual Data Model

The next chapter explains how the four MOPS outcome descriptions are combined together to provide a single overall rating level of environmental comfort for the purpose of retrieving cases from the case-base. Why not save space in the computer and just store this single conclusion (score) about performance? As mentioned before, there is no single universal approach, but many ways to evaluating building performance. There is a need, therefore, to provide flexibility to allow for evaluations other than my own. This representation scheme stores all of the "raw" data values to support the multi-dimensional evaluation that I use, without excluding other approaches.

Even within my own retrieval approach, dividing the outcome data provides increased flexibility. I can allow for cross-comparison or weighting of attributes based on the source of the data (qualitative, quantitative or a combination of both). In this way, future Users of WEDA can "override" the pre-sets. They could choose, for example, to place higher importance the opinion of occupants than the performance results assembled from measuring devices when retrieving cases.

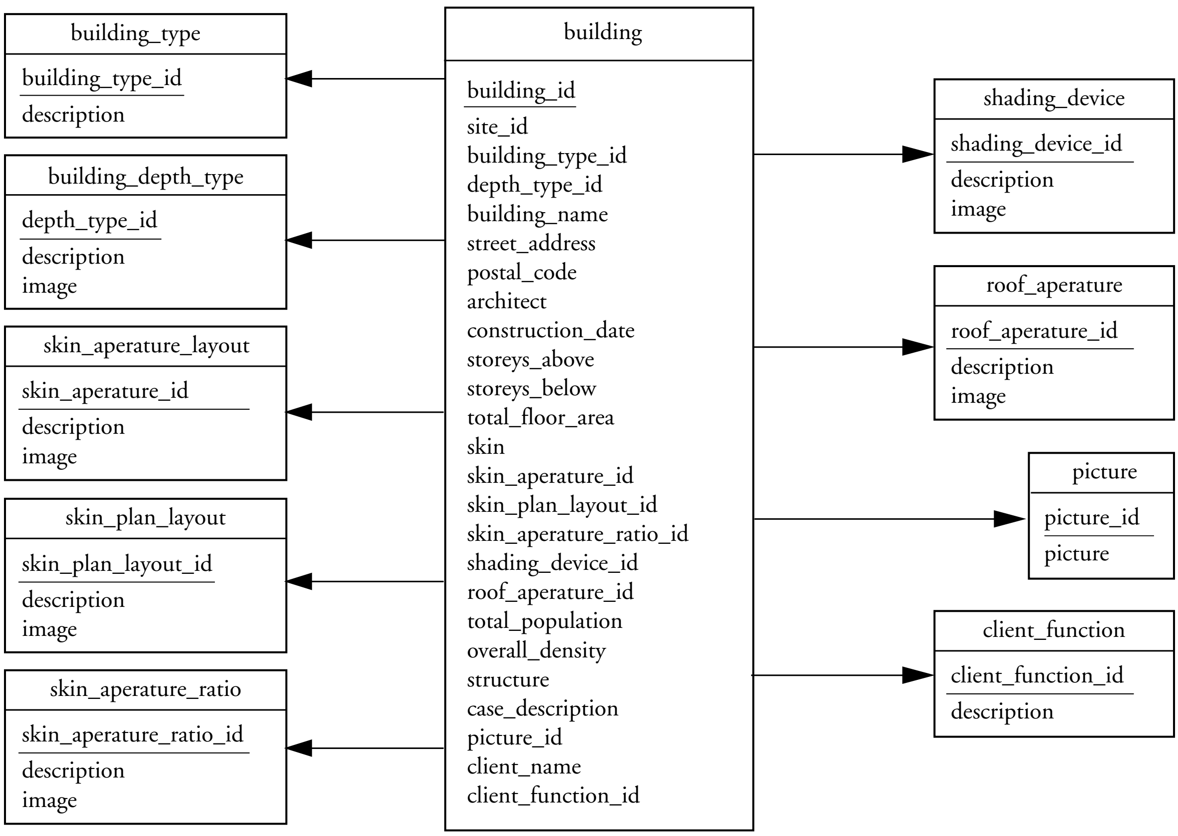


Figure 5.21. Example of the use of Design Models in WEDA Cases

Design Models. Many of the features of design case descriptions I need to store in the case library are shared. For example, an electric lighting system is usually described in terms of the same set of elements: lamp type, luminaries, and optics with some varying features (such as dimmable ballasts). Rather than storing every design case in its entirety, I use a hierarchical representation where general knowledge about a case resides in a design model and specific knowledge unique to the case is stored in the case itself. In this way, each case becomes an instance of a more general model (e.g., workplace). Several design models for environmental building systems and workplaces have been incorporated into WEDA's case data model to make the description of the cases more efficient (Figure 5.21.).

V.6. Summary

Figure 5.22. provides an overview of the tasks described in this Chapter used to create cases. Each rectangle represents a process. Horizontal lines indicate inputs-outputs. Items below each rectangle indicate who and how the process is done. Items above each retangle indicate controls. The following text is a summary of observations made during this process.

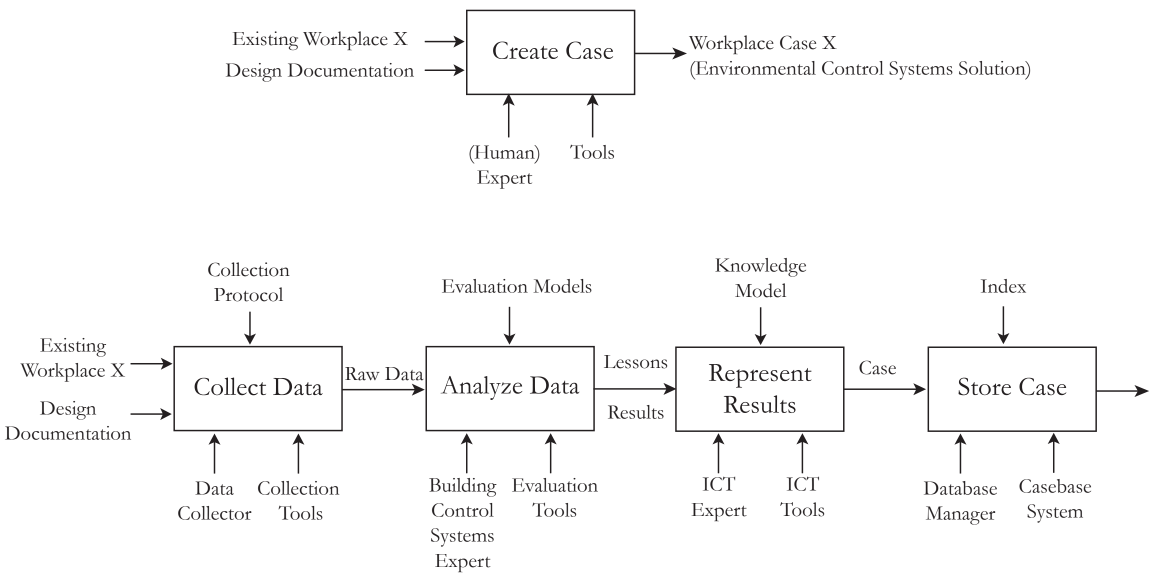


Figure 5.22. Process Model for Creating Cases

The body of knowledge in a CBDA is found in its case-base. Like any expert, the more a CBDA knows, the more useful it is going to be. Finding easy ways to collect case data is critical not only to the initial "seeding" of a case-base, but also for the purposes of keeping a CBDA up-to-date with new information in the future.

As I began trying to create suitable cases of workplace environments I found it was hard to access existing POE data and there was no universal approach for collecting new POE data. Unable to find a satisfactory source of data, I developed a "POE toolkit." It is derived from an extensive survey of domain literature, adaptation of existing measurement methods, consultation with experts, and experimentation in the field. The objective of the toolkit is to provide architects with a fast and easy way of collecting, compiling, and representing POE cases to put into a CBDA.

Deriving the POE toolkit took considerable time and effort. Though not perfect, the pilot studies demonstrate it is possible to use the POE toolkit to generate some interesting and useful knowledge about environmental comfort in the workplace. Some of the key lessons-learned through this investigation are:

Case content. It is surprisingly easy to collect a lot of data. To save both time and resources, identify and collect only the information you need. A case should contain problem, solution, and performance outcome. Begin by establishing key performance indicators for the performance topic being studied. Attribute-values are not always text, but come in a multitude of media types. Often a picture (or sound) is indeed worth a thousand words.

Case selection. Cases with unusual (innovative) solutions or that have unexpected outcomes are the most interesting and educational. Select "stand-out" cases to study or sets of similar solutions to compare and contrast.

Case collection. It is difficult for many architects to collect their own case data, but not impossible. The POE toolkit shows how an architect can use existing methods to easily capture useful case data. It would, however, require an ongoing commitment of resources. The alternative, extracting workplace cases entirely from POE data found in secondary sources such as domain literature or consultant reports, is uncertain. Such information is often proprietary and incomplete in terms of case content. The best approach is to combine previously done POE studies with new field measures, as done in Pilot Studies 3 and 4, which is both efficient and effective.

Case analysis. The performance description is the most important part of the case. The clearest overall picture of performance comes from multi-dimensional analysis (i.e., MOPS approach) of both quantitative and qualitative criteria. The primacy of occupant opinion should always be considered. As Case C demonstrated, just because a building system is energy-efficient does not mean it is good for people.

Good evaluation models are essential for extracting the knowledge out of the collected data. It is important to note that some of the environmental evaluation models reviewed during the course of my study were based on the out-dated vision of a work environment as a designated room or cubicle where someone goes to work from nine to five. Such models are unable to cope with some of the new forms of non-territorial, asynchronous work environments explored in my study. New criteria has to be, and will continue to need to be, invented.

Case structure. Design data models inherently add another layer of knowledge to the data. This has both advantages and disadvantages. Models organize case data so that it is easier to search and add new cases. Once established, changing the model is difficult. Case structures are separate from the case content and are hard-coded into the computer.

Improving Knowledge Acquisition in Practice

This chapter demonstrated how it is possible for even a single practitioner to build and sustain a small CBDA case-base, given a set of easy-to-use POE tools. Creating better tools that encourage design practitioners to collect POE data represents what could be a significant step in trying to build up "virtual" bodies of knowledge. What could practitioners do with all of their newly collected data? Rather than relying on current the "top-down" approach that relies on governments and official bodies to commission the collection of performance data by a select group of experts, a large on-line case-base of environmental design practice could efficiently be built "bottom-up," with the on-going contributions of many building professionals and organizations around the world.

In my experience of building my own case-base I found while most professionals were intensely interested in acquiring new knowledge, there were only a few willing to share their POE data. Unlike other professions, such as medicine and law, where precedents are regularly used to build domain knowledge, the building profession treats its knowledge as a commodity, even referring to it as "intellectual property." In the end, the biggest barrier to overcome in acquiring case knoweldge might not be the lack of expertise or equipment, but motivating professionals to share their knowledge.

CHAPTER VI

Recalling Design Knowledge

The Case Retriever

A CBDA system contains two types of knowledge – the knowledge contained in the cases and the knowledge used to retrieve the cases from the case-base. The former is represented in the case-base and the latter is represented in what is referred to in this study as the "Case Retriever" [CR] or "Case Retrieval System." The CBR system's CR ensures cases are retrieved efficiently and are relevant to the problem at hand. How do we know when a workplace case in the case-base is relevant to the architect's current problem? This chapter describes two possible approaches for recalling workplace case information from the case-base.

VI.1. Remembering: Mapping Problems to Solutions

At the core of a case-based approach to problem-solving is the idea that rather than trying to solve a problem from first principles, it is much easier just to remember the answer. A CBR system's Case Retriever has no answers, but it does know how to find them.

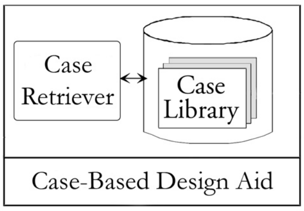


Figure 6.1. The CBR Case Retriever

As described in Chapter IV, the typical retrieval strategy used in CBR is to compare the description of a new problem with its stored problem descriptions, identify the most similar one, and then find and retrieve its stored solution. In order to allow WEDA to be more strategic in the way it responds to design problems, I proposed that instead of comparing design problem descriptions, the system's Case Retreiver should compare performance outcomes, as shown in Figure 6.2.

The single and multi-requirement-element performance paths, introduced in Chapter IV represent two performance-based strategies for mapping stakeholder requirements to building solutions by matching desired with actual performance outcomes. This chapter discusses the application of these two strategies to find and retrieve workplace cases stored in the case library.

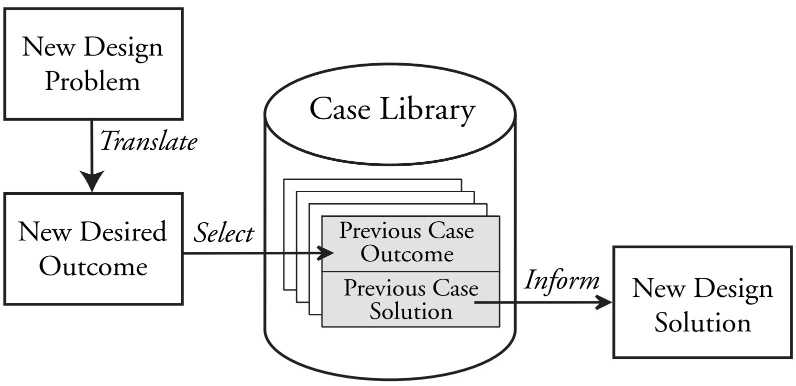


Figure 6.2. Mapping new problems to solutions through performance outcomes.

VI.2. Strategy 1 – Matching Performance Criteria

In Strategy One, the retrieval of cases is achieved through the comparison of individual *desired* and *measured* performance attribute-values. The procedure for case retrieval, shown in Figure 6.3, consists of the following steps:

1) Determine new stakeholder profile and identify key functions,
2) Create required performance specification,
3) Check source case to see if it has been measured for required performance,
4) Calculate distance between desired and actual performance value for each attribute using similarity function (see next sub-Section VI.2.1),
5) Calculate overall average distance for each case, and
6) Rank and retrieve list of cases to User, beginning with most similar (smallest distance).

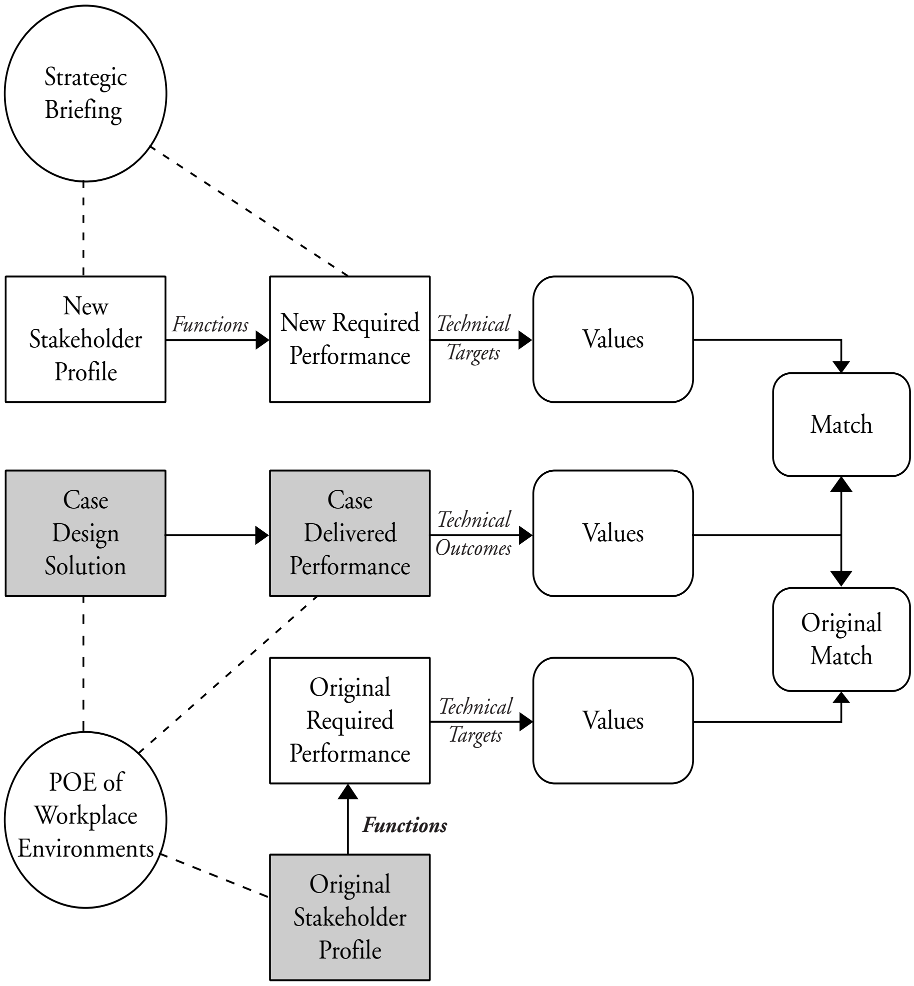


Figure 6.3. Performance Attribute-Value Comparison

This retrieval strategy is based on translating a new workplace brief into a set of target outcome values that can be matched with measured POE values of workplace cases. Because it is a comparison of outcomes, it is possible a workplace built for a purpose different from that of the new stakeholders may be recalled. For example, the performance of an insurance company workplace in the case library might also satisfy the new performance requirements for a call-centre client. The "original match," also shown in the model, is a comparison of the fit between the workplace case and its actual occupants. How well the case design performance fit with its actual use is also interesting for a design decision-maker to know.

VI.2.1. Nearest Neighbour Retrieval

Nearest neighbour formulas calculate the similarity between *attributes-values* of the target case and a source case. The formula determines the overall relative *distance* of the new case (the *target case*) to cases in the case library (the *source cases*). During the comparison the scale is usually normalized to a number between 0 and 1 (where 0 means no similarity and 1 is an exact match).

In Strategy One, the Agent compares each attribute-value of the target case with the attribute-values of the source cases in the case library. The method for comparison is a *similarity function*. Different similarity functions are needed for comparisons between attribute-values that are discreet (for example: 24°C, 300 lux, or 60dBA) or in ranges (e.g., 20-28°C, 100-600 lux, or 50-70 dBA).

Discreet Values The comparison of discreet values with other discreet values is obviously straightforward. Let us say that the indoor temperatures of three source cases in the case library are: Case A = 15°C, Case B = 30°C, and Case C = 24°C. If the performance brief indicates the target indoor temperature should be 24°C, then only Case C should be selected from the case base. This is expressed by the similarity function (1):

$$\begin{aligned}&\textit{value } T_i \longrightarrow \textit{value } S_i\\&\textit{if } T_i = S_i \textit{ then} \longrightarrow \textit{select } (\textit{distance} = 1)\\&\textit{else} \longrightarrow \textit{do not select } (\textit{distance} = 0)\end{aligned} \qquad (1)$$

T = target value (demand search criteria)
S = source value (supply from case)
n = number of attributes in each case
i = an individual attribute from 1 to n

Ranges. Most of the time, demand requirements are not expressed in discreet values, but in ranges of performance. For example, an acceptable lighting level for computer tasks is 300-500 LUX. Similarly, the supply performance of indoor environments (stored in the cases) can also be expressed as a range. For example, a dimmable lamp may provide 0 – 500 LUX. The following approach allows the Agent to compare the similarity of one range with another.

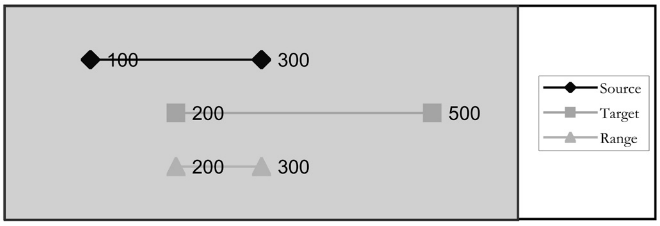


Figure 6.4. Overlapping Ranges

Comparing ranges is composed of two steps: *overlap* and *mapping*. The first step is to see if the requested target range and the range stored in a case overlap each other as in Figure 6.4. If so, the ranges are considered to "match." Non-overlapping case ranges and target ranges are irrelevant to each other and, therefore, do not match. To calculate overlap (i.e., find out if a case is relevant or not) the Agent uses equation (2).

$$\textit{range } T_i \longrightarrow \textit{range } S_i$$
$$R_{\min} = Max\ (S_i\ (\text{min}),\ T_i\ (\text{min}))$$
$$R_{\max} = Min\ (S_i\ (\text{max}),\ T_i\ (\text{max}))$$

$$\textit{if } (R_{\min} < R_{\max}) \textit{ then} \longrightarrow Match = TRUE$$
$$\textit{else } Match = False \qquad (2)$$

T = target case (demand search criteria)
S = source case (supply example from case-base)
n = number of attributes in each case
i = an individual attribute from 1 to n
Match = overlap of range values for attribute *i* in cases T and S

When cases ranges match the Case Retriever calculates how much the two ranges overlap each other (P = Proportion Overlap). This helps to determine how close a match has been made (Equation 3).

$$range\ T_i \longrightarrow range\ S_i$$

$$P = \frac{R_{max} - R_{min}}{S_i\,(\text{max}) - S_i\,(\text{min})}$$

where

$$R_{max} = \text{min}\,(T_i\,(\text{max}), S_i\,(\text{max}))$$
$$R_{min} = \text{max}\,(T_i\,(\text{min}), S_i\,(\text{min})) \qquad (3)$$

P = proportion of overlap of ranges

VI.2.2. Mapping Functions

The second aspect of the range-to-range comparison is mapping where the ranges overlap using a *mapping function* (m_i). In other words, do the ranges overlap at the beginning, end, or middle? The significance of where ranges overlap changes depending on the criterion (*i*). My study uses four different mapping functions: A, B, C, and D to cover the potential retrieval situations I have identified for workplace environment design. These Functions are described in more detail in the following sub-Sections IV.4.2.1-4). The general equation (4) is as follows:

$$Match\ Rate = P * M$$

where:
P= proportion of overlap
M= mapping function
T = target case (demand search criteria)
S = source case (supply example from case-base)

$[S_1, S_2]$ = *source case range*
$[T_1, T_2]$ = *target case range*

$$P = \frac{\text{max}(S_2, T_2) - \text{min}(S_1, T_1)}{|T_2 - T_1|}$$

$$M = \frac{M_\chi(T_1) + M_\chi(T_2)}{2}$$

where
M_χ = *mapping function A, B, C, D*

(4)

VI.2.2.1. Mapping Function A

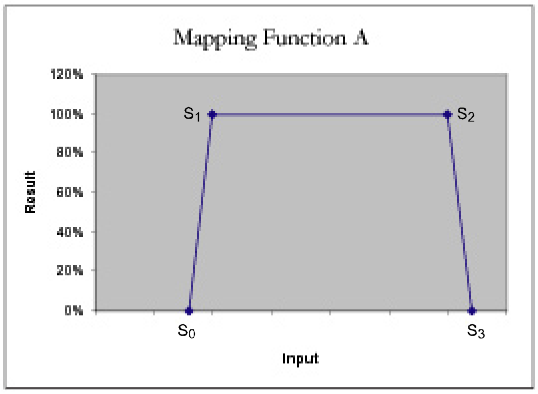


Figure 6.5. Mapping Function A

Mapping Function A is used to retrieve cases where the desired range of outcome and actual case outcome should be more or less the same (give or take a certain percentage on either end). For example, where a work task is very important, requiring a high level of concentration and precision, occupants can be very sensitive to environmental short-comings (under and over-performance). For computer screen users too much light can cause glare, whereas not enough light can make reading tasks difficult. Air quality can also work this way; not enough ventilation, and a room feels stuffy, too much and papers start to flutter on the desk.

VI.2.2.2. Mapping Function B

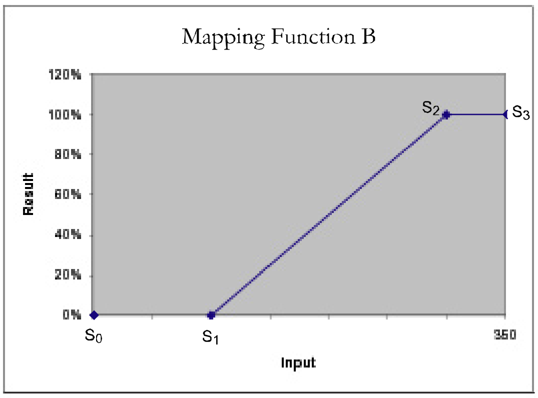


Figure 6.6. Mapping Function B

Mapping function B is used when the preferred match is towards the higher end of the range. For example, in terms of visual comfort for reading tasks it is better to have more light than less light. For a Target Range of 100-

500 LUX, lighting systems that are capable of providing higher amounts of light (300-500) would be more desirable (i.e., a better match) than those that are still within the range, but produce less light (100-300 lux).

VI.2.2.3. Mapping Function C

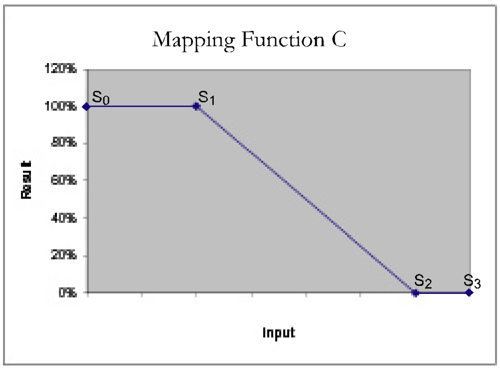


Figure 6.7. Mapping Function C

Mapping function C is used when the preferred match is towards the beginning of the range. For example, in terms of acoustical comfort, quieter workplace environments are generally preferable over noisier ones. Within an acceptable requirement range of 30-60 dBA, a better match would be an environment that is closer to 30 dBA than 60 dBA.

VI.2.2.4. Mapping Function D

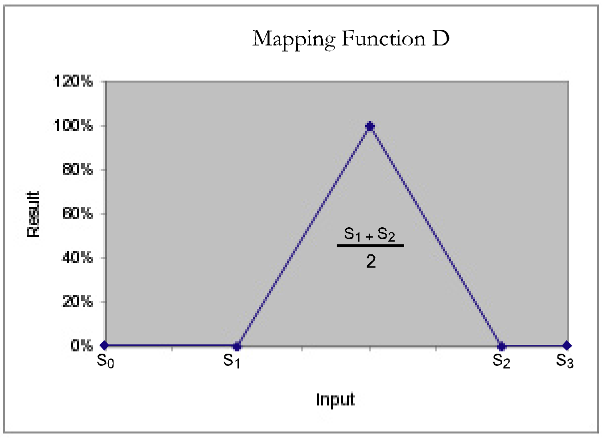


Figure 6.8. Mapping Function D

Mapping function D is used when it is desirable to match towards the middle of a range. This type of matching is very similar to discreet value matching, but it allows for values that are slightly more or less than a particular ideal value to also be considered. For example, although an ideal temperature for working may be 24°C, environmental systems that provide temperatures in the range of 22-26°C are also acceptable. Obviously, in terms of thermal comfort a match at either end of the acceptable range (too cold or too hot) is less desirable than a match towards the middle.

VI.2.3. Ranking, Thresholds and Weights

In its present form, case retrieval using Strategy One considers all attribute values equally. Cases are ranked according to the average of target matches. Because the distance in similarity is normalized to one (1), it is easy to do another calculation to express the overall match in terms of a percentage (i.e., average of 0.7 x 100 = 70% match). A simple refinement to increase the weighting of some attributes over others would be to allow the User to control which attributes are used in the calculation. Another alternative would be to compare other sets of attribute-values, such as the similarity between the new and original stakeholder profiles, functional requirements, or both.

VI.2.4. Advantages and Disadvantages

The main advantage of retrieval Strategy One is that it works directly with the POE measures. This allows the User to easily see what performance they are looking for and what the performance of the case is. For example the desired technical target "lighting level=500 lux" is compared with the actual measured outcome "lighting level=600 lux" in the case. This kind of transparency is educational for inexperienced Users and desirable for experienced Users who can fine-tune their search.

One of the disadvantages of this approach is it places equal importance on all attributes. In general, thresholds or weightings are not part of retrieval. The case retrieval relies on the assumption that the most suitable indoor environment is going to be one with the best average of all performance indicators considered. In some situations, this is not always true.

Beyond the matching functions, a Strategy One case retrieval system has very little embedded knowledge. Instead, it relies on the intelligence implicit in the indexed attributes themselves. These attributes have been elicited from current building evaluation methods during knowledge modelling (see Chapter IV). Each attribute is intended to represent a key indicator of indoor environment performance. While these may be enough to enable the Case Retrieval system to provide a good match for general level decisions, a CR system with more embedded knowledge about multiple performance attributes may be able to provide a more in-depth view.

VI.3. Strategy 2 – Matching Performance Profiles

In Strategy Two, cases are retrieved based on a comparison of performance rating scales. Illustrated in Figure 6.9, the procedure followed for case retrieval is as follows:

1) Determine new stakeholder profile and identify key functions,
2) Create desired performance specification using rating scale and request thresholds (sub-Section VI.3.2.),
3) Check source case to see if a rating level has been assigned (if not, a comparison cannot be made with the new desired performance rating level),
4) Calculate suitability between desired and actual performance profiles using rating level (sub-Section VI.3.1),
5) Calculate overall average rating for each case, and
6) Rank and retrieve list of cases to User, beginning with most similar rating levels.

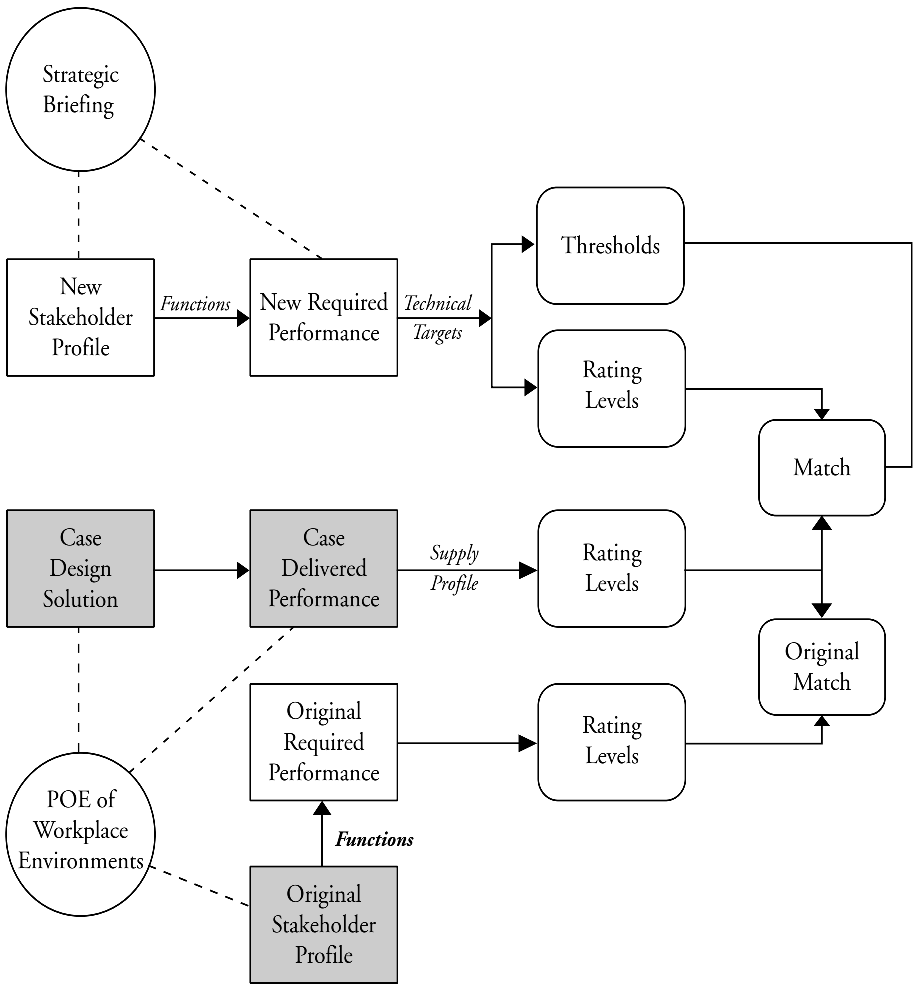


Figure 6.9. Comparison of Performance Rating Levels

VI.3.1. Rating-based Retrieval

This strategy for retrieval is based on the Serviceability Tools and Methods® [ST&M®]. In Chapter IV, I introduced ST&M as an approach to multi-attribute knowledge modelling. ST&M can also provide a means for recalling cases. ST&M is a series of "macro-processes" that support "the strategic decision-making of occupant requirements about a space and about facility serviceability" (International Center for Facilities, 2003). One of the applications of ST&M is to help organizations find the best match between their own requirements and the capabilities of a building or portfolio of buildings they are considering to rent, lease or purchase. I have adapted the ST&M approach to find the best match between stakeholder requirements and the capabilities of workplace environment cases in a case library.

The matching process is a relatively straightforward calculation of the similarity between demand and supply profile serviceability rating levels This process is illustrated in Figure 6.10.. Rating levels, as explained in Chapter IV, are on a scale of 0-9. The best fit occurs when the two profiles match each other. Differences in rating levels suggest "gaps" in performance, where either the capacity of the facility is less or more than required by the stakeholder.

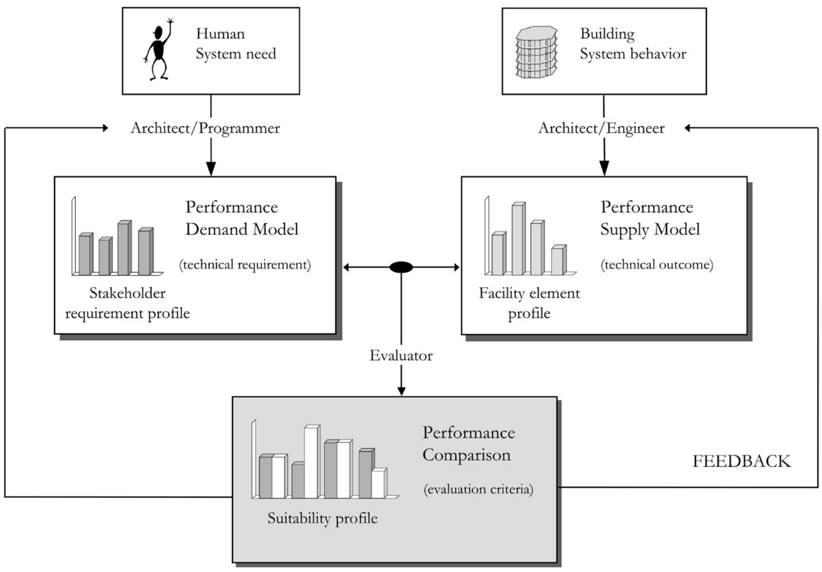


Figure 6.10. Comparison of Performance Profiles Consisting of Rating Levels

VI.3.2. Generating Rating Profiles

Before the matching process can occur, the performance profiles need to be generated. Table 6.1. is an example of a stakeholder requirement profile for a high tech office environment created using the ST&M rating approach. A "T" indicates the threshold, or minimum rating level, for a particular requirement. In Table 6.1. you can see how each profile has "bundles" of requirement *items* relating to a requirement *cluster*. The organization and content of the profile shown here is slightly different than ST&M. It has been adapted to incorporate the results of the performance-path modelling of workplace performance evaluation domain knowledge explained in Chapter IV.

Table 6.1. Requirement Profile (High Technology) adapted from (Davis & Szigeti, 2003)

HSL: Individual Well-being				Rating Level									
Group	Cluster	Item		1	2	3	4	5	6	7	8	9	
Health & Comfort	Visual Environment	Lighting Quantity & Glare									T		
		Lighting Quality									T		
		Distant & Outside Views									T		
		Occupant Control								T			
	Acoustic Environment	Privacy & Speech intelligibility								T			
		Distraction & Disturbance								T			
		Vibration								T			
		Enclosure									T		
	Thermal Hygric	Temperature & Humidity									T		
		Occupant Control									T		
	Indoor Air	Indoor air quality									T		
		Indoor air supply								T			
		Occupant Control								T			

In my requirement-element model building evaluation knowledge is classified hierarchically into levels of *group*, *cluster*, *item*, and *attribute*. *Items* and *attributes* correspond to "topics" and "features" in the ST&M approach.

There are currently over 100 topics and 240 features in ST&M. Only two topics from ST&M, relating specifically to individual effectiveness and indoor environments, are considered in my study.

What knowledge does WEDA's Case Retriever need to make a "Health and Comfort" profile? The ability to rate the level of performance requirements and workplace performance outcomes relies on the existence of *serviceability scales*. For each item in the performance profile I created a set of matched serviceability scales containing *attributes* to describe functionality and case performance. As mentioned previously in Chapter IV, the new scales refer mainly to the ST&M scales, but are not exactly the same. The knowledge content in the original ST&M scales, consisting of five descriptions written in natural language, had to be broken down into "Agent-readable" attributes-value pairs. The original ST&M scales are also based almost exclusively on American ASTM standards whereas the case data collected for my study is European. So I have modified some of items and attributes contained in the ST&M scales to incorporate attributes for European and other building environment evaluation standards included my own POE strategy described in the previous Chapter V. An example of one of these scales is provided in Table 6.2..

Rather than generating supply profiles every time a case is recalled, facility rating scales can be applied to cases when they are first entered into the case base. In this way, performance supply profiles are generated once and then stored with each workplace case. While standard demand profiles can also be stored in the system, some Users will want to generate a profile specific to their client. This means the Case Retrieval system needs to be able to help such Users dynamically generate a requirement profile before undertaking the matching procedure.

Requirement profiles, as shown in Table 6.1., are made up of clusters of requirement items. Each requirement item, as shown in the example provided in Table 6.2., is made up of multiple attributes. To determine the rating level for any item in a requirement profile, one must assign values for each of the requirement attributes.

I propose to interactively generate rating levels by having the Case Retrieval system query the User about their functional requirements in relation to each indoor environment requirement scale. The CR then uses rules to relate the answers to the appropriate rating level. In this approach each User query consists of set of functional and operational questions about their client, each with a multiple-choice list of answers to choose from. Each answer corresponds to a requirement scale rating level.

Table 6.2. Matched Occupant and Facility Rating Scales for "Lighting Quality"

Occupant Requirements Scale (Lighting)			**Rating Level**	**Facility Performances Scale (Lighting)**				
R_1 Occupant Task	**R_2** VDU Use	**R_3** Tolerance Lighting Defects		**T_1** Illumination Level [LUX]	**T_2** Control	**T_3** Visual Defects	**T_4** Glare	**T_4** Personal Glare Control
Different Everywhere	VDU & Paper	None	**9**	300-700	Flexible	None	None	All
Different in Parts	Long periods VDU	Low	**7**	300-700	Adapt-able	None	Some	Possible No cost
Single Visual Task	Several VDUs	Medium	**5**	500-700	Fixed	1	Yes	Possible Small cost
Non-visually demanding	Few VDUs	High	**3**	700-1000 or 0-300	Fixed	2	Yes	40-60% Stations None
Minimum Requirement			**1**	700-1000 or 0-300	Fixed	≥ 3	All	None
Minimum Threshold =								

The example query, shown in Table 6.3., is used to determine the occupant rating level for "Lighting Quality" that is part of the performance profile for "Visual Environment." The Case Retrieval system asks the User about their client's task, computer screen use, and tolerance for lighting defects (R_1, R_2 and R_3 in Table 6.2.). For the question "how often do occupants use computer screens?" the User can choose from one of the six possible answers from "high level of VDU and paper" (rating level 9) to "not at all" (rating level 1). By averaging all of the rating levels assigned to each answer, the Case Retriever determines a final rating level for "lighting quality." The Case Retriever then can compare this requirement rating level with the facility rating levels for "lighting quality" stored with cases in its case library.

This procedure was implemented and tested in the WEDA prototype. A snapshot of the user interface, that includes help-screens to explain each question the Agent asks, is shown in the next chapter (Section VII.5.1).

VI.3.3. Advantages and Disadvantages

The advantage of Strategy Two is that it incorporates a facility for retrieving cases and for generating performance briefs. The normalization of multiple

Table 6.3. Example Query to Define Requirement Rating Level

	CR-System Question	**User Response**	**Rating Level**	**Average Rating Level**
$\mathbf{R}_1$	"How many different visual tasks do(es) the occupant(s) do?"	"Different in parts"	7	
$\mathbf{R}_2$	"How often do occupant(s) use computer screens?	"Long periods at working on computers"	7	7.6
$\mathbf{R}_3$	"How tolerant are occupants to defects in lighting?"	"None"	9	

attributes into a rating scale of discreet values between zero and nine allows for easy comparison between supply and demand values.

The disadvantage of Strategy Two is that its strength of having much more imbedded knowledge is also its weakness. Ostensibly, the "smarter" the Case Retrieval system is, the more efficacious its searches are likely to be. At the same time, the use of rating scales makes the procedure for matching less transparent. What if the User disagrees with the underlying descriptions and theories used by the computer to determine requirements for facilities? Maintaining the knowledge in the CR can also be a problem. Unlike case knowledge that is stored in a data base, control knowledge is generally "hard-coded" into the CBDA system by a programmer, which makes imbedding large amounts of knowledge time-consuming and harder to access and change.

VI.5. Summary

WEDA is a case-based computer system that simulates the judgement and behaviour of a human or an organization that has expert knowledge and experience in a workplace environment design. As such, it has two parts: (1) a knowledge base containing accumulated experience in the form of workplace cases and (2) a set of rules for applying the knowledge base to each particular situation described to the program. This latter part is referred to in this study as the *Case Retriever* or *Case Retrieval System*.

The Case Retrieval system is important because its expert knowledge is embedded into the system. Many of the decisions about the way cases are indexed and how they are retrieved are not made by the User of the system, but by the programmer and systems designer. Cases contained in a CBDA case-base can represent outstanding design solutions, but they will not work for every application. Just like its human counterpart, it is the ability of the CR system to choose the most relevant cases from its accumulated experience that makes it useful to the User.

This part of my study shows how a Case Retrieval system using a performance-based approach offers a good way of matching stakeholder requirements to design cases stored in a case base. A performance-based CR relies not on prescribing a physical solution to any given problem, but finding a desired outcome. This allows for much more flexibility in retrieving a wider variety of solutions stored in the case base. In this chapter I provide two potential strategies for retrieving cases using a performance-based approach.

The first strategy is the most straightforward of the two. In it, the Case Retriever creates a performance specification consisting of desired values for technical targets and compares these with the actual values of POE measurements stored with each case. Retrieved cases are ranked based on average number of attributes they match. The underlying knowledge model is derived from POE methods and building performance standards.

The second strategy is more complex. Instead of using individual attribute-values, the CR uses bundles of attributes to create a performance specification consisting of serviceability rating level scores. Retrieved cases are ranked according to the comparison of target scores and scores stored with each case. The underlying knowledge model is derived from modified ST&M serviceability rating scales.

Of the two approaches described here, Strategy Two has several distinct advantages for decision-making. Unlike Strategy One, it uses non-metric satisfaction criterion, no summation across scales, and takes into consideration multiple evaluation criteria to describe performance. As such, it more closely represents the kind of naturalistic decision-making of a human expert who is more likely to compare patterns of requirements with certain levels of outcomes, rather than look at specific measures. Additional knowledge needs to be included in both the case-base and Agent to accommodate the rating system.

A limitation of both strategies is that, in a performance-based approach, the knowledge is only as good as the underlying building evaluation methods and standards used to describe the quality of workplace environments. As discussed in the previous chapters, WEDA's knowledge model (Chapter

IV) is an integration of several well-established international and national standards. Despite this, many aspects of the current evaluation methods, including ST&M, remain theoretical and require further validation. A possible avenue for future research could be to develop a facility for WEDA's Case Retriever, like any expert, to learn new knowledge.

CHAPTER VII

Theory into Practice

What a working system might look like

This chapter describes the results of the final stage of this research in which a demonstration version of WEDA was created and then tested with a focus group. This simulated version of WEDA reveals how the proposed CBDA support system might actually look like. The creation of WEDA-demo highlighted many of the practical issues involved in creating a working CBR system while also providing an opportunity to get feedback from potential users. The end of this chapter reflects on this experience and its implications on the future for WEDA and systems like it.

VII.1. WEDA-demo Goals and Objectives

WEDA is intended to be a tool used during strategic briefing and conceptual design of workplace environments. It helps architects determine environmental performance requirements and select building climate system concepts. As a stimulative CBDA it promotes creative decision-making and enhances learning about a decision situation.

The first goal of creating the demonstration version of WEDA, or *WEDA-demo*, is to help validate its theoretical approach by giving potential users something "real" to evaluate. The second goal is to identify practical issues that tend to only arise when moving from theory to practice.

The objective for this stage of the research is to implement and test three key components of WEDA-demo:

1) translation of a functional brief into performance brief of technical targets,
2) retrieval and ranking of workplace cases, and
3) browsing of workplace cases.

Section VII.2 restates the goals for WEDA established by the Definition Study. This is followed by a description of the implementation process and its results in sections VII.3 through VII.5. Section VII.6. describes the focus-group testing workshop and its key outcomes. Finally, in Section VII.7., I reflect on the experience of taking theory into practice.

VII.2. End-User Requirements for WEDA-demo

What should WEDA do for its User? One of the first things I did in developing the concept for WEDA was to determine what would be key functions from the end-User's point of view. Based on the Definition Study (Chapter IV), I described what a fully implemented version of WEDA should ultimately be:

- **Accessible and Educational.** A web-based CBDA that provides multi-media workplace design cases to inform, illustrate and inspire early design decision-making,
- **Relevant.** The designs expertly retrieved based on a capacity to satisfy the functional performance needs of the stakeholders,

- **Up-to-date.** Constantly and easily added to by constituents, the case-base contains a wide variety of up-to-date, strategically evaluated designs, and
- **Easy-to-use.** Working with WEDA is similar to working with human engineering expert or organization that has vast experience in POE and indoor environmental systems design. The only difference is the expert is a computer and their knowledge is stored in a case library.

In 1998, two years following the completion of my Definition Study, a European Union-sponsored focus-group met in a series of Workshops to consider the role of KBS systems in design practice. The "EIKS workshops" identified the following set of general priorities for what a KBS system should do to help designers make decisions about energy efficient building systems:

1) Provide support for decision-making,
2) Not a design tool, but a communication tool; act as a design assistant,
3) Serve the expectations of owner/developer and user, (e.g., be easy to understand),
4) Contain experience gained from good projects and also what not to do,
5) Generate and compare alternative solution,
6) Provide warnings and highlight problem areas,
7) Allow checking against rules and regulations,
8) Provide various levels of detail, depending on the viewpoint of the disciplines involved, and
9) Be able to make approximations based on the preliminary information available, e.g., "rules of thumb" (Groot & Pernot, 1998).

Though it is relatively general, this list is included to show what design practitioners identified as their needs in terms of intelligent systems support. Of these, the first four functions are covered in the conceptual vision for WEDA. It is interesting to note that once end-Users were confronted with a real system, described later in this chapter, during testing some features identified as important in the above list fell away, and others were re-enforced. Like any design process, systems development is an iterative process of refinement, and user-feedback is part of quality control. Future system developers should consider the lesson learned here: include end-Users throughout the process or risk creating something they do not want or need.

VII.3. Implementation

The WEDA-demo is created with a suite of tools from SYBASE and webpage editing software. Each WEDA component was implemented separately to make the prototyping process more manageable. The three main components of the WEDA-demo are (Figure 7.1.):

1) Case-base Manager (add cases)
2) Case-Base Design Reasoner (retrieve cases)
3) Case-Base Browser (explore cases)

The processes and data for WEDA (described in Chapter IV) were first modelled using PowerDesigner™. The tools within this package, Process Analyst™ and Data Architect™, are easy to use and support a variety of well-known modelling approaches. Data Architect™ was particularly useful for this project because it is capable of taking a conceptual data model (a generic representation of the database tables) and generating a physical data model for any database. It is also possible to reverse engineer an existing database back into a conceptual model, which is very useful for further analysis and maintenance of the database.

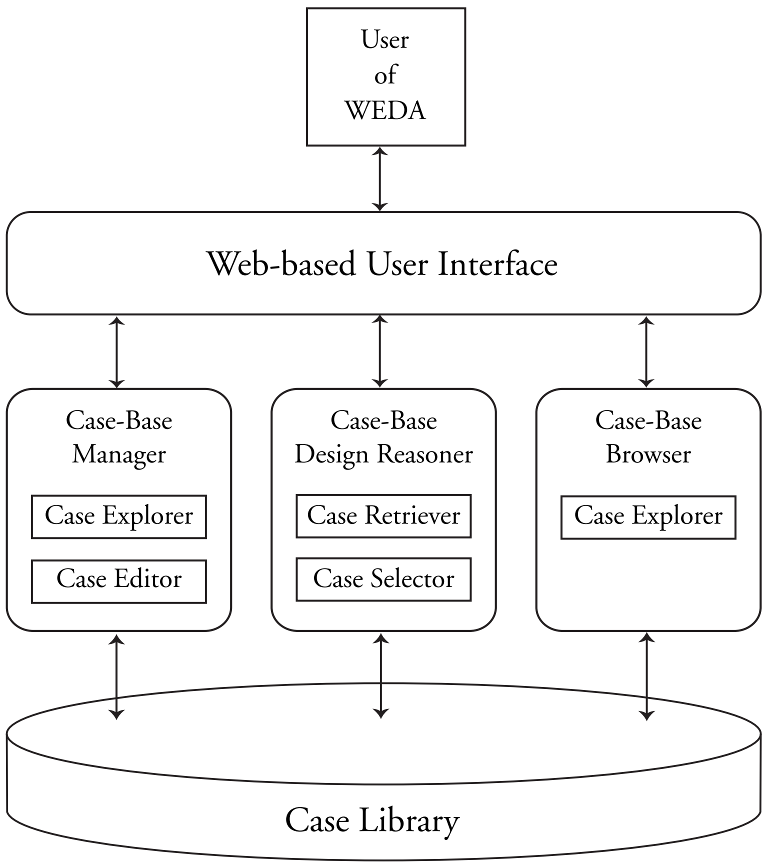


Figure 7.1. WEDA Components

Adding cases. Initially all case data was entered directly into the case-library using an SQL tool. Later, to allow anyone to input new case data into the case library, an on-line case-base editing component was programmed in JAVA. This component was the last to be prototyped and was only partially implemented by the time the project ended.

Retrieving Cases. WEDA-demo's user interface is created using PowerBuilder™ (Version 7.0). The WEDA-Client is the interface for case retrieval and links to the case browsing environment. PowerBuilder™ also provides the tools a database administrator needs to maintain and edit case information stored in a relational database (*SQL Anywhere*).

Applications created using PowerBuilder™ are independently executable. They run without PowerBuilder™ being installed on the system. This made it easier to distribute prototype versions of WEDA for testing.

Browsing Cases. WEDA-demo's case-browsing environment was created using FrontPage. For WEDA-demo case data was temporarily typed into HTML pages (it was initially unlinked to the database). Creating the browsing environment as a separate component was done to allow for rapid development and testing. In a final version of WEDA, the data in the HTML pages would be built dynamically by drawing case information directly from the database.

In the WEDA-demo, only the case-browsing environment is currently platform-independent. The WEDA-demo is initially deployed for a Microsoft Windows operating system environment. Ultimately, WEDA is intended to run over the internet and all components would be platform-independent. A future implementation of the system would need to be implemented in a different programming language such as JAVA.

Users and Roles. Procedures are required to handle different user-types. For WEDA there are three user types: the *System Administrator*, the *Case Base Editor*, and the *Human Architect-User*. Each have different access rights when it comes to case modelling, case acquisition, case maintenance and case review.

The *System Administrator* has the highest access rights in the system. S/he maintains and updates the domain model as well as user-administration.

The *Case Base Editor* is responsible for case maintenance and case approval. The Editor checks to see if new cases submitted are relevant. S/he removes redundancy and ensures consistency in the case base. S/he can modify the value ranges of attributes but not the domain model itself.

The *Human User* has the lowest access rights in the system. This is the person who uses the system to help determine design solutions for their clients (workplace clients). S/he can also be the person who contributes new cases to the case library. The main tasks for the Human User are entering their client requirements, case review and new case acquisition.

VII.4. Knowledge in the WEDA-demo

To create an initial case-base for the WEDA-demo, the POE data collected from the five offices of Case Study One (see Chapter V) were used. For each office room, POE information was collected for over 150 attributes. The key area of interest in these office designs is their innovative lighting systems. Therefore, WEDA's initial case representation and retrieval focuses primarily on lighting goals and requirements.

Cases are stored as records in a relational database, with a field for each attribute-value according to the data model described in Chapter V. Each design case has information relating to its:

- stakeholder brief (function),
- physical solution (structure), and
- MOPS performance outcomes (behaviour).

To simplify data entry, normalized tables of design elements were set up according to building system models to allow for the use of drop-down menus as much possible. Information is hierarchically arranged according to the SBPPE and POE knowledge models (found in Chapter IV), which includes Architectural System Levels, Human System Levels, Building System Levels and their related performance outcomes. The resulting data organization is a combination of Function-Behaviour-Structure [FBS] and design model approaches (see also Chapter III - *memory organization*). Fields in the database can be left blank if the complete records for a particular design case are unavailable.

A variety of data-types are supported, from simple numbers to 360° panorama images. Some performance indicators indirectly related to lighting (e.g., indoor temperature) were also included in the case. A complete case representation used in WEDA-demo can be found in Appendix C.

VII.5. User Interface of WEDA-demo

The User-interface of WEDA-demo is based on the analogy of an architect, the system's Human User, talking with an environmental engineering consultant, replaced by WEDA-demo's Case Retrieval system, to get inspiration and advice about their new workplace environment design problem. The "conversation" begins with the Case Retriever asking the Architect-User what the general goal of the environmental system should be (e.g., energy efficiency). The Case Retrieval system then proceeds with asking key questions that help it to translate the workplace stakeholders' functional problem into a performance-based brief consisting of technical targets the new design must meet.

The brief allows the Case Retriever to search through its "portfolio of project experiences," represented in WEDA-demo by cases in a case-library. Selecting from the most relevant examples it finds, the CR then suggests a list of previous design solutions, beginning with one most likely to provide the best fit, and ending with the one likely to be the poorest fit in terms of performance. The Architect-User can then select from the list to ask for more detailed information. The CR shares its experiences using illustrations from its portfolio of cases, providing the Architect-User with alternatives, stories, and criticisms of similar situations to explain what happened when such a design problem was encountered in the past. The Architect-User may then select a solution or several solutions to review in more detail as a starting point or inspiration for developing a conceptual design. Later, after the new project is built and evaluated, it is added to the "portfolio" of cases.

Given this description, it is easy to see the exchange between WEDA-demo and its Human User is highly interactive. As such, the interface between WEDA-demo and its User becomes very important. Each interaction with WEDA-demo is illustrated in Figure 7.2.. The right-hand column identifies each process step from problem representation to a problem-solving representation. The former is a performance brief, and the latter is a case or set of cases to use in establishing an initial conceptual design. The left hand column identifies an interface between the system and the User. As shown in the diagram, each process requires some information from the previous process step as well as input from the User. The information passed between the User and WEDA-demo is shown beside each arrow. Each interface box in the diagram represents a window or series of windows used to collect information from the User.

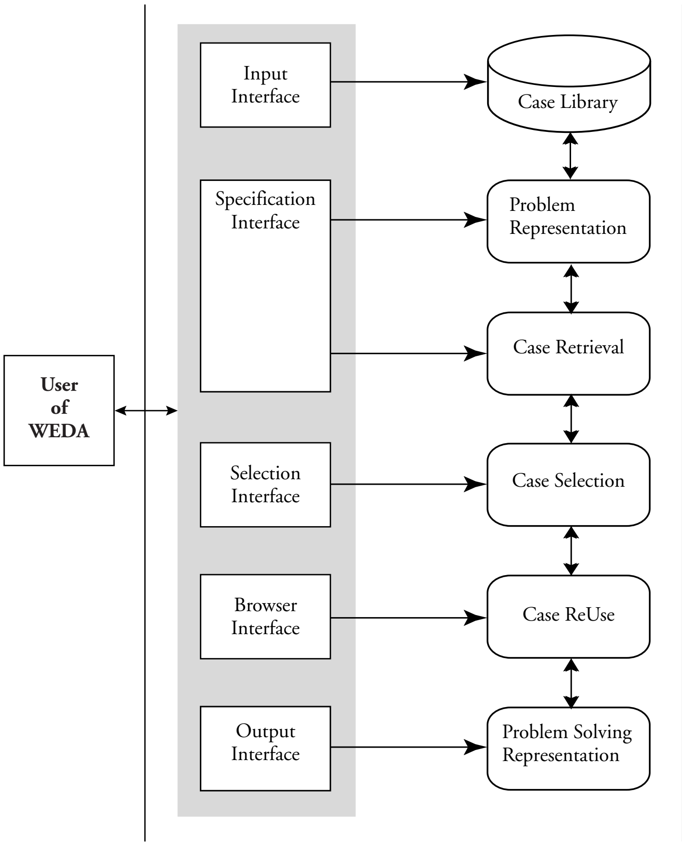


Figure 7.2. WEDA Interface and Processes

The specification, selection, and browsing interfaces have been implemented in the WEDA-demo. The following sub-sections (VII.5.1. to .5.3.) provide examples of the interface screens and describe the underlying processes for each interface in more detail

VII.5.1. Specifying the Target Problem (Indexing)

Situational assessment is the translation of one communicating partner's vocabulary into the other's. In CBR systems, situational assessment classifies the target problem and matches it to the appropriate indices of the memory structure before retrieving cases. This procedure is useful when vocabulary within the problem domain is unique to different reasoners. In my study, I use situational assessment to address the differences in vocabulary between architects and indoor environment engineers and to deal with a variation in detail and abstraction for different design stages. That is, to connect (detailed) POE source cases with (abstract) conceptual design target specifications.

WEDA-demo can "talk" with an Architect-User about six lighting design goals (see Table 7.1.). For each goal WEDA asks a unique set of questions. For example, to determine the minimum light level for a workspace WEDA-demo asks about the work task, the age of the occupant, the importance of the task accuracy, and the background of the visual task. Depending on the answers provided, WEDA-demo automatically creates a set of desired technical performance targets (e.g., minimum light level of 300-500 lux).

Table 7.1. Lighting Design Goals in WEDA-demo

Lighting Design Goals
1. Provide minimum light level requirement
2. Maximize visual comfort
3. Individual control of lighting and glare (open plan areas)
4. Individual control of lighting and glare (cellular offices)
5. Optimum distant and outside views
6. High energy efficiency

WEDA-demo's problem specification screen, shown in Figure 7.3., consists of 5 components:

1) performance goal; where the Architect-User selects a lighting design goal
2) client's operational and functional brief; where the User enters answers to questions specific to the lighting goal
3) indoor environment performance target(s); generated by WEDA
4) dynamic help window; where detailed explanations are automatically displayed for each question, and
5) performance weighting; allows the User to specify that additional importance be given to specific technical targets when judging similarity between the architect's target information and case information.

This last component was only partially activated in the WEDA-demo. Case retrieval can either be based on the similarity to all technical targets or problem desicription (no technical targets).

VII.5.2. Retrieving Cases (Similarity and Ranking)

The retrieval of cases from WEDA's case-base takes place in two steps. As described in the previous sub-Section, the first step is the translation of the Architect-User's functional description of the workplace problem into a performance specification consisting of technical performance targets. This translation is done automatically by WEDA-demo. The target

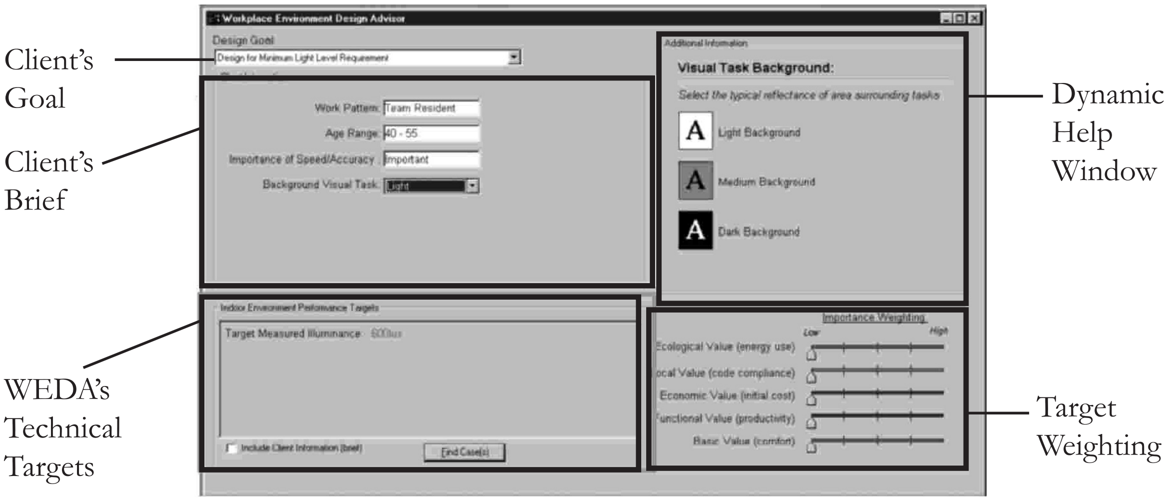


Figure 7.3. WEDA-demo Problem Specification Screen

attribute-values (demand profile) are then shown to the User (lower left area in Figure 7.3.).

The second step is to retrieve and rank cases by comparing the technical targets representing the desired outcome with the actual outcomes of the workplace cases stored in the case-library. This process is done in the background by WEDA's Case Retrieval system using the "Strategy One" procedures described in Chapter VI. Although I generally consider strategy two to be the superior of the two matching procedures, for the purposes of rapidly prototyping the system, it is easier to implement the individual attribute-value matching procedure of strategy one. For more information about both procedures refer to Chapter VI.

Once WEDA has completed the second step, it opens the screen shown in Figure 7.4.. The case selection screen displays a list of retrieved workplace cases ranked in order from best to worst, in terms of the fitness for use represented by the similarity between the desired and actual performance outcomes. The performance attribute-values for each case are also displayed.

Two measures describe to the User how well the case's actual performance attribute-values match with the desired technical targets. These are: *distance* and *percentage (%) match* (see also Chapter V). Distance indicates how closely each individual attribute value in the retrieved case matches the target value on a scale of 0 to 1 (with 1 being the farthest away or a poor match). Percentage match indicates similarity in terms of a percentage value.

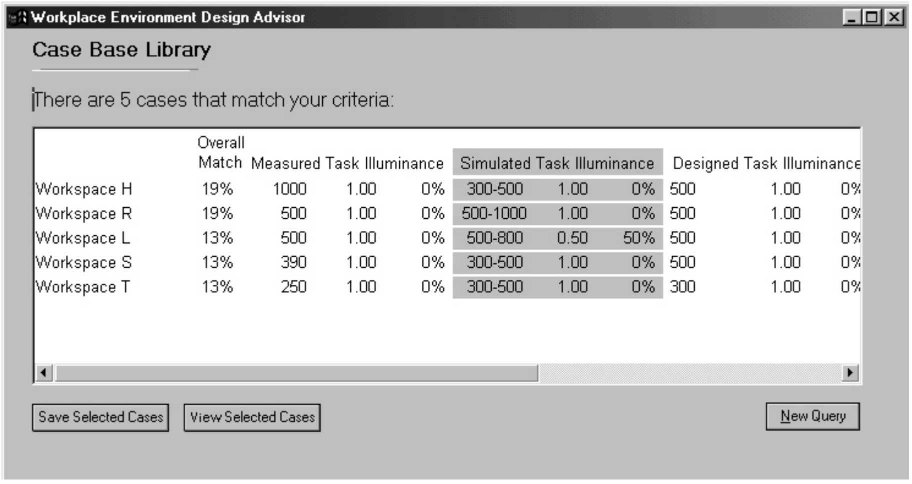


Figure 7.4. WEDA-demo Case Selection Screen

Once the Architect-User has reviewed the list of cases, they can choose to: view any of the retrieved cases, save case(s) into a folder (called a "portfolio"), or return to the previous window and make a new query with a different set of requirements.

VII.5.3. Selecting & Browsing Cases

WEDA-demo's browsing interface is used to view and explore retrieved cases in more detail. It is intended to represent how an architect might review a design portfolio. This digital design portfolio has the added benefit of multimedia technology that allows images, drawings, stories, sounds, performance evaluations, and other design information to be dynamically linked together and easily navigated.

Selecting a case from WEDA-demo's case selection screen (Figure 7.4.) opens a frame-based browsing environment (Figure 7.5.). Within this environment it is possible to explore a panorama (a 360° digital image) of the case and click on various objects in the picture. When an object is clicked (e.g., light fixture) additional information appears in the "information" frame (i.e., manufacturer, energy performance). In another frame a "map" or 2D plan views of the room are shown. A directory is provided that allows users to directly "jump" to information of interest.

VII.6. Evaluation of the System

A final evaluation workshop was held to test the two systems built as part of the Building Evaluation Research program: WEDA-demo and ILSA. Thirteen invited experts from the Dutch lighting and building industry

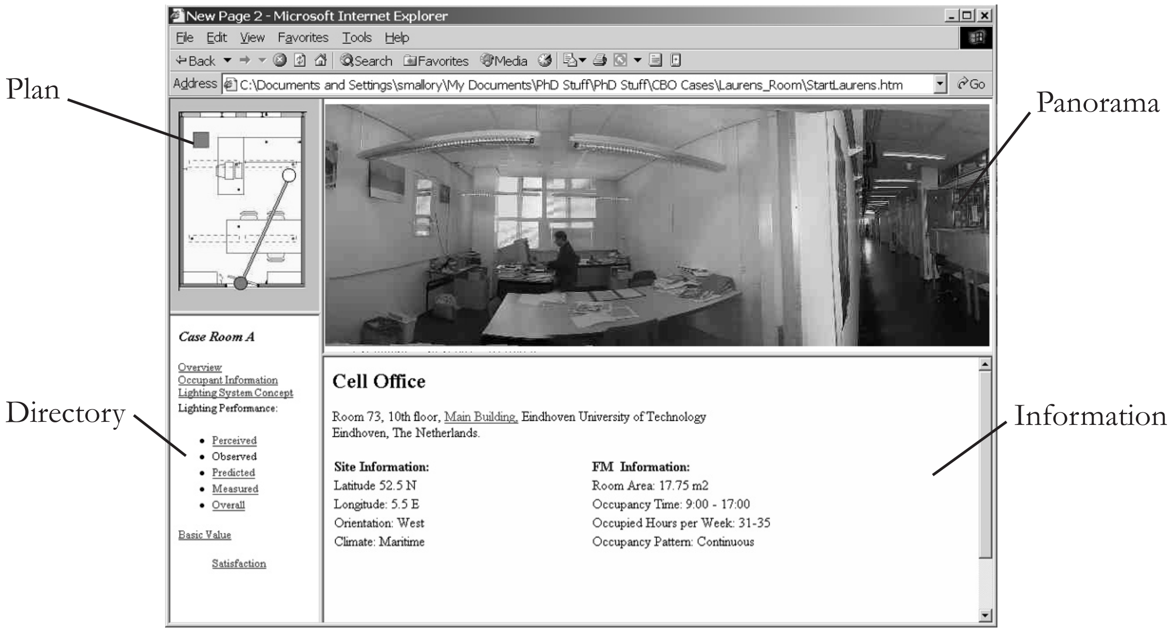


Figure 7.5. WEDA Case Browser Screen

tested WEDA-demo during the morning session and ILSA in the afternoon session. This workshop was held in electronic Group Decision Rooms [GDR] located in the Faculty of Technical Management [TEMA] at the Eindhoven University of Technology.

VII.6.1. Goals

The goal of the focus group workshop was to obtain feedback and validate the WEDA-demo's case- and performance-based strategies for supporting strategic workplace environment design (lighting component). Getting input from real Users was considered to be a very essential part of the development of WEDA. Facilitating a participatory design approach gave the problem-owners a voice in the design and content of the system. This is particularly important in indoor environmental systems design since technologies and expertise is constantly evolving and changing.

The objectives of the WEDA workshop session were to:

1) **Validate Knowledge (Retrieval) Model** – Is the retrieval of cases based on performance-based technical targets appropriate and effective?
2) **Validate CBR Approach** – Would the retrieved POE cases support the strategic design of workplace lighting? Is the content of cases useful and valid? Is there a better way to present case information? What features should a future system have?

VII.6.2. Approach

The workshop was undertaken in a special electronic meeting room designed for group decision-making. The "Group Decision Room" of the Faculty of Technical Management [TEMA] allows for a maximum of 15 participants on site (with potentially more participants located off-site). Participants are provided with their own networked computer and special software through which they can communicate anonymously with other participants. A chairperson, or meeting instigator, leads the meeting. The chairperson is supported by a facilitator who is not involved in the content, but helps in the planning and running of the meeting (Weatherall & Nunamaker, 1999). The facilitator also is a technician who helps participants use the computers and Group Decision software.

The chairperson's computer screen is projected onto a central wall by a projector. During the WEDA-demo workshop I, as the chairperson, used two sets of computers and projectors, one to project the software demonstration and the other for the group decision software. In this way participants could simultaneously view the prototype as well as the contents of the current discussion. The projector is also used to show the agenda, and (interim) results of each discussion. A photograph of the WEDA-demo workshop setup is shown in Figure 7.6..

The motivation for using this approach was to take advantage of the benefits of electronic meetings over traditional style meetings. These advantages are listed in Table 7.2..

Figure 7.6. Group Decision Room Testing of WEDA-demo

Table 7.2. Benefits of Electronic Meetings

Maximize Time Available	◊ clear structure to meeting ◊ parallel input (everyone can contribute simultaneously without waiting for their turn to "speak") ◊ shared input (agree/disagree with what is already said without repeating input) ◊ larger numbers of people can participate
More/Better ideas produced	◊ anonymity can help creativity ◊ commitment is high because comments are written down and very public ◊ user opinions can be collected quickly and accurately ◊ voting helps to focus discussion and build consensus
Getting Results	◊ electronic record is immediately available

From: (Weatherall et al., 1999) p. 21

VII.6.3.Timetable

Table 7.3. shows the timetable for the evaluation workshop. The session began with a general welcome and an introduction to the use of the Group Decision Support System software. This was followed by a presentation of this research project. The prototype WEDA was used to demonstrate how the knowledge model might be implemented in a CBR system.

In the first validation task participants were asked to evaluate WEDA-demo's retrieval environment. After being shown a demonstration of WEDA retrieving cases, participants were asked to comment on a list of five specific concepts that define the way WEDA-demo retrieves cases.

In the second validation task participants were asked to evaluate WEDA-demo's case browser environment. A copy of WEDA's browser was provided at each computer station so participants could "play" with the software independently. During a brainstorming session participants were asked to respond to general questions about the navigation and content of the cases as a means of supporting early design decision-making.

As a final task, participants were asked to summarize their results. An electronic voting session priorizes all of the issues raised during a GDR session. During this activity participants review all of the comments and suggestions made during the validation sessions and then vote to priorize the issues they feel are most important. The outcome of this task is a list of the top 10 issues to address in potential future research about WEDA's knowledge model and CBR approach.

Table 7.3. WEDA Workshop Agenda

09:30 AM	Introduction Participants & Group Decision Room
10:00 AM	Presentation: WEDA Development
10:20 AM	Validation of WEDA-demo Retrieval
11:00 AM	Coffee/Tea Break
11:15 AM	Brainstorming (Improvements)
11:35 AM	Validation of WEDA-demo Browser / Case Content
11:55 AM	Brainstorming (Improvements)
12:10 PM	Summary of results (vote)

VII.6.4. Results

To those unfamiliar with electronic meetings, it is astonishing how quickly a large amount of information can be collected from a group using this technology. During a two hour period, over 750 comments and suggestions about WEDA-demo were provided by fifteen participants to the Group Decision Support system. Following the meeting this information was analyzed by organizing it under the following categories:

- Potential Risks and benefits,
- Suggested improvements/user requirements, and
- Key issues

The following sub-sections provide a summary of the results from the evaluation workshop. A detailed report of the workshop activities and results are provided in (Groot & Mallory-Hill, 1999).

VII.6.4.1. Evaluation of WEDA-demo's Retrieval

A summary of the risks and benefits associated with the way WEDA-demo retrieves cases are provided in Table 7.4.. The focus-group felt a key benefit of WEDA-demo's retrieval strategy is that it efficiently generated a (technical) performance brief from a (architectural) functional brief for non-environmental engineering experts (e.g. architects). The participants also identified it was beneficial to use performance brief criteria as selection criteria for cases because it "provide[s] an objective way of fitting client needs to a solution...." The major potential risks associated with using the system relate to giving a non-expert a "false sense of security." Environmental engineering experts in the group felt there should be more transparency in the way technical targets are calculated (e.g. show which standards were applied). Experts also desired more control to allow them to over-ride WEDA-demo's automatically generated performance brief in order to fine-tune or enter their own technical targets.

Table 7.4. Summary of participants response to retrieval strategies

Strategy	
1. Translating the brief into technical targets automatically.	Risks ◊ The relationship between brief and targets is not explained to non-experts; ◊ False sense of security; ◊ Experts will want to enter technical specifications directly; ◊ Some client information may not be available in advance (e.g., age of occupants).
	Benefits ◊ Non-experts are able to specify targets without knowing the standards; ◊ Trial and error & help window provide insight into relationship between requirements & design; ◊ All the necessary client information used to make lighting decisions is collected.
2. Use technical targets to locate cases.	Risks ◊ Non technical targets such as aesthetics, psychological and sociological factors are not covered; ◊ Potentially too detailed for early stage of design.
	Benefits ◊ Provides an objective way of fitting client-needs to a solution rather than decision-making based on personal or other non-technical ideas.
3. Use multiple technical targets to describe performance.	Risks ◊ Non-experts are unable to weight / judge individual aspects in relationship to each other potentially makes the program over-complicated; ◊ Limits potential matches
	Benefits ◊ More realistic representation (lighting quality is more than just a single criteria like lux); ◊ Able to design for complicated and sensitive situations.
4. Use a percentage and "distance" to describe level of match for multiple targets.	Risks ◊ Overall % match oversimplifies; ◊ Concept of "distance" is not understandable; ◊ False sense of precision; ◊ It is not clear which criteria are more important than others.
	Benefits ◊ Overall % match gives a quick result; ◊ Percentages work well in communicating how a case performs on various levels.
5. Case values that do not match the targets exactly or fit within ranges are 0% match.	Risks ◊ User has no control over setting sensitivity of match (e.g., relaxing precision); ◊ Potentially overlook interesting cases.
	Benefits ◊ Helps to narrow down cases to only those relevant for your solution; ◊ Rules out cases that may conflict with other requirements by over/under performing.

The suggestions for improving WEDA-demo's retrieval put forward by the group relate to either to modifications to the current interface (making it easier to use) or ideas for adding features (see Table 7.5.).

Table 7.5. Suggested improvements to retrieval component

Interface Changes
◊ Use questions to lead to goals; ◊ Use more descriptive options for setting client requirements (e.g., not "type 1"); ◊ Make proposed technical targets modifiable; ◊ Use more graphics and pictures; ◊ Hide technical information; ◊ Make it more obvious how a user can improve a match (broaden search); ◊ Make it easier to do and compare multiple retrievals using different goals and/or sets of targets; ◊ Improve appearance of retrieved cases window (information is hard to understand)

Additional Features
◊ Allow users to enter unique sets of technical targets; ◊ Possibility to search on more than one brief; ◊ Allow users to select from which standards or norms to apply when setting targets (or automatically set by asking for building location); ◊ Allow non-experts to express requirements "by example" (picture or concept); ◊ Allow user to rank technical targets (most important to least); ◊ Provide glossary of terms; ◊ Provide different user levels (perhaps determine expertise level with a list of questions); ◊ Add searches based on non-technical targets/goals; ◊ Allow cases to be retrieved based on shape, room size or window location.

VII.6.4.2. Evaluation of WEDA-demo's Browser

The focus-group identified that one of the main benefits of WEDA-demo's web-based browser environment is that it is instructive. It encourages Users to explore technical problems by navigating through the outcomes of individual cases, explore alternatives and potentially challenge assumptions. (See also summary of browser evaluation results in Table 7.6..) The main short-comings of the browser environment for supporting environmental design highlighted by the focus-group testing relate primarily to the scope and re-usability of the mainly performance-based case content in the WEDA-demo's small case-base. The current *case coverage*, the distribution of case information across the subject area, is limited. For example, the types of lighting systems in the cases are different, but the differences in performance of the systems are more subtle. Users found it difficult to determine what might be a "better" solution because case performances could not be compared with each another or original search criteria. Once

Table 7.6. Participants evaluation of WEDA-demo's browser

Questions	
General Impression of WEDA's browsing environment (ease of use and case content).	Risks ◊ Pictures of lighting solutions can be misleading (depend heavily on the quality of photography); ◊ Issues of air-conditioning and temperature are difficult to communicate in this way because they are invisible; ◊ Reliability of such a small POE sample is questionable (e.g., one user's satisfaction); ◊ Panoramic image is overkill; ◊ Daylighting is not covered adequately;
	Benefits ◊ Internet is a well-known environment for people to use; ◊ Good for showing concepts to clients; ◊ Multi-media approach gives a well-rounded description of performance and encourages exploration of case; ◊ Panorama is intuitive to use; ◊ Accessible remotely.
Potential as a "feed-forward" tool (post-occupancy evaluation lessons into new design).	Risks ◊ "Ready to use" solutions are more practical than teaching cases.
	Benefits ◊ A very strong tool for exploring various solutions and their characteristics (not for providing solutions).

a "better" solution is determined based on performance, Users expressed a desire to be able to re-use the case solution directly, rather than only re-use the lessons-learned.

The suggested improvements to WEDA-demo's browser (Table 7.7.) emphasize a need for better integration of WEDA-demo's components and to expand case content, particularily in terms of graphics (illustrations, photos, visual explanations of performance).

Table 7.7. Suggested improvements to browser

Interface Changes
◊ Link text to objects (e.g., lighting components) in picture; ◊ Show target values directly on image (lux levels, luminance ratios); ◊ Add information on room finishes; ◊ Improve integration of retrieval and browsing environments (perhaps provide "expert" explanation why this is a good match for the designer); ◊ Provide management summary (user selected criteria); ◊ Provide more images showing the case with different lighting conditions (with and without daylight, sunny day, winter, afternoon...etc); ◊ Show the same lighting concept being used in different situations (e.g task, locations); ◊ The "dart chart" should show cases being better when closest to "bulls eye"; ◊ Add sound clips to explain acoustics; ◊ Add more pictures and visualizations; ◊ Add spoken comment by user and/or designer; ◊ Add more views of exterior (shading, overhangs); ◊ Give more information on specific requirements that had to be fulfilled (stories?) by the architect; ◊ Discard any information that is case-specific (only relevant to that particular case in that particular situation).
Additional Features
◊ Ability to compare different lighting solutions in the same room; ◊ Expand multi-media features by adding hyperlinks to other sites on the internet (movies, films, audio files); ◊ Ability to compare different cases (side by side); ◊ Provide list of alternative solutions that may also have worked (or were considered and discarded); ◊ Combine case based tool with a tool based on rules, experience, and common knowledge.

VII.6.4.3. Summary Activity

Due to time constraints, the group was unable to complete the summary activity in the group decision room. Instead, a mail-out survey form containing all of the suggested improvements to the WEDA-demo was sent to all participants. Participants were asked: "if you had limited time and resources, which modifications would you make?" The return rate of this survey was 38% (5 out of the original 13 participants). The top recommendations are provided in Table 7.8. and Table 7.9.. Each recommendation is weighted according to the percentage of respondents who chose the recommendation, and the average of all rankings (1 being the highest priority to change).

Table 7.8. Suggested Changes to Retrieval

Top Recommended Changes to Retrieval
1. Provide weighting for the different criteria. (100%, Avg. 3.2) WEDA-demo currently uses multiple targets to describe performance but all criteria have equal importance. 2. Explain/show why underperforming cases do not match targets and how they potentially could be changed to improve performance. (80%, Avg. 3) Cases with performance outcomes lower than technical targets set by the user are considered to be underperforming (suggesting failure). 3. Also use non-technical targets to search for cases, for example: aesthetics, perceived wellness, etc. (80% Avg. 3.5). WEDA relies almost exclusively on "engineering" measures to describe performance. 4. User should be able to over-rule exclusion of over-performing cases. (60% Avg. 2.6) WEDA currently considers cases with outcomes that exceed technical targets set by user as over-performing (suggesting wastage). 5. Questions should be used to determine user's overall lighting goals. (80%, Avg. 8.5) WEDA currently allows the user to select their lighting goal. 6. Ability to compare different cases (side by side) (60%, Avg. 7). WEDA provides a side-by-side comparison of retrieved cases in relation to a given set of technical targets, but it does not allow for side-by-side comparison of multiple search scenarios. 7. Ability to use cases to locate cases (40% Avg. 5). WEDA currently searches on technical targets determined from answers about the client's brief entered by the user. Example briefs or case solutions could allow for faster searching ("more like this one…"). 8. Ability to enter technical targets directly (20% Avg. 1). WEDA automatically generates technical targets.

Table 7.9. Suggested Changes to Browsing

Top Recommended Changes to Browsing
1. Display technical information with each case (uniformity of light, intensity (lux), colour of light, daylight percentages). (100%, Avg. 5.6) Technical target retrieval information set by user is not compared with the technical outcomes of the actual case in the browser. 2. Provide link to retrieval tool so that the criteria can be viewed and adjusted. (80%, Avg. 3.5) In the current version of WEDA, the link to the browsing component from the retrieval component works one-way (opens selected case in browser). 3. Show different lighting effects (60%, Avg. 3.3) WEDA-demo's case-base contains a limited number of photographs/simulations of each case. Cases cannot be adapted in anyway. Therefore, users are not able to change conditions or elements in the room (such as select different lighting, see the room at night, turn off some lighting). 4. Show task view under different lighting conditions (60% Avg. 3) WEDA currently only shows a limited view of the task plane and under only one (original) lighting condition. 5. Show impression of view at different times. (60%, Avg. 4.3) WEDA main view of the room is taken at a single time of day and season. 6. Design suggestions / help to improve the lighting concept. (60%, Avg. 4) Each case contains POE information (i.e.,,original commentary by evaluators). WEDA does not have the capacity to make design suggestions or suggest remedial work to make an existing case fit a new design situation. 7. Glossary of Terms. (60%, Avg. 7) The text of the cases is can be technical in nature, but currently there is no help or glossary function for defining these terms.

VII.6.5. Learning from WEDA-demo workshops

The primary goal of the evaluation workshop was to evaluate the ideas incorporated in WEDA-demo's retrieval and browsing environments. Ultimately, I wanted to discover if such a Case-Based Design Aid would be considered useful by experts and potential "end-Users." WEDA-demo proved to be a much more effective way of communicating my concept compared to any theoretical paper or diagram I had presented before. As a result, I am very confident the feedback I received from the focus-group provides a good indication of whether or not a fully implemented WEDA would be useful by potential end-Users. The following are some of the key ideas expressed in the WEDA-demo, and what the participants thought about them:

Support for analysis of a new workplace design situation (WEDA as processing-aid). Users generally agreed that processing of functional requirements into technical performance brief (targets) is helpful, and would support the consideration of indoor environment issues earlier in the design process, epecially by non-environmental engineering experts (i.e. architects). Although it did not appear in the transcripts from the workshop discussions, participants strongly suggested cost attributes (economic model) should be added to the system.

Future implementations should provide more opportunities for differentiating between user expertise. Less experienced users could be given more help to defining overall indoor environment design goals and expert users could be allowed to adjust technical targets to suit their own needs more closely.

Provide access to relevant past solutions (WEDA as memory aid). Multi-attribute retrieval of cases was a good idea in theory that was somewhat disappointing in implementation. The translation of abstract functional information into a technical performance brief (set of technical targets) was successful. It did help to make a connection to the POE information stored in the case-base. A lack of attribute weighting meant it was hard for Users to differentiate between retrieved cases that matched on some attributes and not others. Although detailed match information was painstakingly provided for each attribute variable for each retrieved case — users tended to rely on the first number, the calculated "overall percentage (%) match." A case with a high overall percentage could match well on many variables, but perform poorly in relation to the few variables critical to the user.

Weighting of attributes was originally excluded in the implementation because there is a lack of hard domain evidence to suggest what indoor environmental factors are more important or influential than others in any given situation. Indeed, as any design process evolves, the emphasis changes, and factors that were important at first, become less important or fall away altogether. For example, if electricity costs become lower, energy efficiency becomes less of a priority. This problem pointed to a need for a more flexible approach to indexing to allow users to adjust search criteria as needed. Future implementations, in addition to broadening search criteria would need to allow users to weight attributes and add additional target attributes according to their own needs. For less experienced Users, as one of the workshop participants suggested, searching by example ("more like this one") by moving backwards from the browser environment could prove to be very effective alternative.

Support the creation of an initial conceptual solution. WEDA's strategy for support is to use cases to provide ideas and lessons, inspiring or warning designers and then leaving them to develop their own designs. The repeated request by workshop participants for a way to manipulate retrieved cases suggests WEDA-demo lacked something designers crave – an opportunity to play.

Could a WEDA case provide a fast and initial solution immediately available for editing and modification by the system or designer? Probably not. To allow for adaptation of an indoor environment design solution would require a much more comprehensive case representation. Even with an extensive model, the influences on indoor environment performance are so complex and not completely understood that there would be a risk that, once taken out of its original context, a case would perform differently. To avoid these problems WEDA was always considered to be a module integrated within a larger design environment where further design development and evaluation could take place. WEDA could, however, offer a more playful interaction.

Future implementations of WEDA certainly will need to improve and expand the visual explanation of technical information. For example provide more renderings or photos taken different times of day/seasons, graphic representations of air flow, and so on. A much better interface for side-by-side comparison of different cases and adjusting technical targets needs to be provided so the designer can experiment with different scenarios. In this way patterns of relationship between certain indoor environmental systems, architectural configurations and their impact on performance measures should become clearer.

Support the build up of past solutions. In the initial implementation of WEDA-demo all of the case data was entered into the data-base by hand. Although there is a good variety of data-types, the existing case-base is quite small and adding cases can only be done by a system administrator. Based on my own experience it is not hard to conclude that preparing a case for storage, retrieval (and possibly adaptation) in the current implementation of WEDA would be an arduous task if it were actually placed in an architectural firm. Yet this task would have to be done regularly to ensure the system contained enough up to date information to be useful.

At one end of the spectrum, some developers argue case memory should be automatically accumulated ("mined") by the system as a side-effect of design activities. That is, the system should track what is going on and accumulate the relevant information in the background. Programs such as SEED claim to do this for new designs. It is hard to imagine how such a system will be able to automatically extract what is important from POE's of existing design cases – particularly since this (what a case means or could be used for) is likely to change over time. At the other end of the spectrum Heylighen, Segers, and Neukermans (1998) suggest direct interaction with cases is an opportunity for learning – the activity of trying to index cases helps designers to identify what they feel is important about them. For WEDA my strategy was somewhere in the middle of this spectrum. I tried to conceptualize a simple environment where it is easy to enter cases and make them accessible to as many people as possible. This meant initially placing some limitations on case content, but what would be given up in depth, potentially could be made up with volume.

Implementation of the last of WEDA-demos's components, the "*Build Case*" environment, began after the testing workshop. This JAVA-based component addresses the issue of how multi-media case data could be entered (and updated) directly into a case-base via the Internet. Unfortunately, due to time and technical limitations of my study, WEDA's "build case" environment was never made fully operational.

How well did WEDA-demo perform in relation to its long-term goals described at the beginning of this chapter (Section VII.2.)? What is still left to be done?

Accessible and Educational. *A web-based CBDA that provides multi-media workplace design cases to inform, illustrate and inspire early design decision-making.* Although WEDA-demo has yet to be implemented on-line, it does make knowledge locally accessible "on-demand" and "at the drafting table." Focus-group participants agreed WEDA would provide support for technical requirement analysis of new workplace situations earlier in the design process. Even with a limited database, the potential value of cases in early design decision-making was clear to the group. The participants requested more support for cost analysis and the creation of an initial conceptual solution (adaptation and play).

Relevant. *The designs expertly retrieved based on a capacity to satisfy the functional performance needs of the client stakeholders.* WEDA-demo currently is capable of generating a performance specification and retrieving and ranking cases based on that specification. The current knowledge in the system is limited to lighting goals and its related attribute-values. Focus group participants felt, in the future, all aspects of indoor comfort (i.e., air quality, thermal/hygric comfort, acoustic comfort) would obviously need to be part of a system to support indoor environment design. It may be necessary to also adjust the knowledge model to consider differing climatic, regulatory, and cultural needs of stakeholders. This might be accommodated by developing serviceability scales for various regional standards (see Chapter IV), and using the normalized performance indicators (i.e., serviceability ratings), instead of performance measures, as a basis for matching.

Up-to-date. *Constantly and easily added to by constituents, the case-base contains a wide variety of up-to-date, strategically evaluated designs.* WEDA-demo lacks a facility to allow constituents to add cases, which makes it very hard to maintain. The focus-group anticipated a high number of cases would be needed to provide quality support. Already identified as a potential "Achilles Heel" of any CBDA system, the accumulation of knowledge for WEDA is probably not a question of developing the technology to enter cases, but the willingness of design professionals to collect and then share POE data with each other. For this reason it might be easier to implement WEDA where the constituency is limited to a select group of members, such as within a firm or network of professional-academic research organizations.

Easy-to-use. *Working with WEDA is similar to working with human engineering expert or organization that has vast experience in POE and indoor environmental systems design. The only difference is that the expert is a computer and their knowledge is stored in a case library.* One of the most effective aspects of implementing the WEDA-demo was keeping in mind its original analogy to a conversation between and architect and engineer. This helped to guide both the development of the interface and the explanation of the system to Users. During testing Users seemed to learn how to use the system quickly, find it relatively easy to use, and get results without too much effort. The next generation of computer-savvy professionals may not need, and ironically, even understand such an analogy. The demands of the computer-literate focus-group Users for more control suggests the system needs to respond at multiple levels of expertise, and at the very least, provide transparency with regards to how it makes its selections. A much more visually appealing interface as well as more visual explanation of (technical) information needs to be developed for the graphically oriented Architect end-User.

VII.6.6. Summary

It is easy to conclude WEDA-demo is imperfect. Some of the criticisms raised about the WEDA-demo during the evaluation workshop were inevitable given its prototypical nature. WEDA-demo is not a commercial system, but a "proof of concept." The small number of cases in the system, for example, is a well-known limitation. The cases included in the system were selected not for their merit as "good solutions" but because they were representative of the various types of data that might be used for retrieval as well as for communicating indoor environment information to designers.

A number of other key issues raised at the workshop are more fundamental and need to be considered. This includes the suggestion that designers may only embrace WEDA if it could provide them with solutions rather than simply "ideas" or "lessons." This finding was surprising because both my Definition Study and the EIKS workshops originally concluded that a design-assisting system would be preferred by Users over a design-generating system. There was also some concern expressed over how existing cases (and the knowledge gained from them) may be re-usable outside of certain climatic, cultural, or legal contexts. Could this be overcome with a larger database? Or, is there an inherent limitation of cases — can they only be used in a certain context until performance evaluation measures and methods are universally established?

Despite these concerns, the overall response to WEDA-demo by the workshop participants' was positive and most felt its current shortcomings could be overcome in time. This enthusiasm is particularly evident in the many suggestions and ideas put forward for improving and extending WEDA further.

VII.7. Conclusions and Future Directions

In Tom Kelley's (2001) book *The Art of Innovation* he remarks: "A picture is worth a thousand words….a good prototype is worth a thousand pictures" (p. 112). Prototyping and subsequent testing did prove to be very effective way of increasing my understanding of WEDA and the possible role for such decision-support systems. When I began this project, no-one knew what a CBR system supporting the strategic design of workplace environments would look like or if, indeed, one could even be built. Now we do know, or at least have an idea.

From a technical point of view, it was impossible to fully realize all of the original vision of WEDA. As Kelley (2001) also comments: "prototyping is about acting before you have answers, taking some chances, stumbling a little then making it right" (p. 107). Implementing a prototype computer system, especially for a non-programmer like myself, is not a job for the faint of heart. When I started programming the WEDA-demo I knew what I wanted the computer to do in theory, but I was not certain how to actually make it do it. Computers are essentially stupid, and teaching them to think like humans requires a lot of trial and error. Miss a comma or a variable in the code and you will be presented with a blank screen "stare." Overcoming technical limitations, both my own and that of available technology, took a lot of time and some compromises. The end-result is not an outstanding work of computer science, but it does achieve the desired effect of adequately demonstrating to architect-Users how cases and a performance-based approach can feed-forward knowledge into early design. It would have been nice, however, to have gone through at least one more iteration of prototype refinement with the Users. In hindsight, instead of working essentially from scratch, it would probably would be easier to give up some design flexibility to be able to rapidly prototype using an "expert system shell."

Although I have followed the methodology prescribed for the development of KBS systems, it is not the intention of my study to create a working system. In my mind, the search for better and more efficient CBR systems is a research topic for computer scientists and not design professionals. This methodology, however, has provided a good structure for investigating my question of how to improve knowledge acquisition and application in design practice using a CBR paradigm. Through the system development methodology I was able to develop a system concept to capture the collective POE experience of indoor environment specialists in a case-base and enable architects to access, re-use and potentially extend this knowledge in a reasonably straightforward manner. The general focus-group acceptance of WEDA-demo proves the feasibility, at least at a conceptual level, of a case-based design assistant helping architects to access technical knowledge they need to design better workplace environments.

One of the major challenges of my study has been to try to establish a reasonable model to capture and represent the experience of domain experts. It requires finding the right level of detail to adequately describe the complex relationships but not requiring the collection and entry of overwhelming amounts of information. In my study, I have used POE measurements of building performance as a basis for knowledge acquisition. This has been reasonably successful for describing the relationship between stakeholder requirements and building solutions. It also allowed for the creation of a POE method for collecting case-data. The disagreement about the validity or emphasis of certain indicators of performance, even within the small group of experts consulted in my study, suggests the domain area is still largely theoretical and needing further validation. Future directions for research in this area would be extending the analysis of building evaluation models and techniques to refine the knowledge model and map out new measures of performance.

Realizing a commercially viable WEDA would require the collaborative efforts of both computer scientists and domain researchers. Application developers might consider how to: support the build up and extension of WEDA's knowledge base to include thousands of cases, allow for comparison of cases, accommodate various levels of expertise of Users, and implement the system for web-delivery. Other possibilities would be to integrate WEDA with other environments to allow for more "play" through adaptation, visual explanation through simulation, or exploration through virtual reality. Domain researchers might consider how to improve and expand the current knowledge model by identifying critical measures in building environment evaluation that: provide a means of assigning an outcome to a design solution, provide an explanation of that outcome, determine success or failure, and predict a design solution's capacity to solve future problems. The development and integration of an economic model to evaluate the cost implication of building environmental performance in WEDA's cases would be a particularly significant contribution.

CHAPTER VIII

Discussion and Conclusions

This chapter discusses the original contributions this research and offers recommendations for supporting the strategic performance-based design of workplace environments with the AI paradigm "Case-Based Reasoning." These contributions include the development of knowledge models to connect POE with early design goals, a toolkit for collecting POE data on workplace environments, strategies for retrieving case data, and WEDA (a prototype Case-Based Reasoning Design Aid).

VIII.1. Overview

The goal of this doctoral research has been to determine the conceptual feasibility of using an "intelligent" computer tool to improve the transfer of POE knowledge into new design cycles. This project combines reviews and analysis of relevant work published by others, knowledge modelling, Post-Occupancy Evaluation and computer simulation of mock-up and real office environments, and prototype testing. This work has led to the development of a performance-based knowledge model to connect POE with early design goals; a "toolkit" for collecting POE data on workplace environments; and a prototype on-line computer tool called WEDA-demo. This research shows how an artificial intelligence technique known as Case-Based Reasoning might efficiently bring knowledge gained through POE in reach of design decision-makers during the critical early stages of design. Improving knowledge transfer between design cycles is intended to help to reduce risk and promote the growth of new knowledge to improve the quality of workplace environment design.

VIII.2. Summary and Discussion

At each stage of this investigation many lessons were learned. The sections following provide an overview of the topics investigated, research contributions, and a discussion of findings.

VIII.2.1. Review of Case-based Design Support

My review of domain literature (Chapter III) points out the potentially significant and supportive role Case-Based Design Aids offer for supporting early design decision-making. From an implementation point of view, in disciplines where explicit domain models do not exist (such as design), a case-based system makes knowledge elicitation much simpler. Even partial case-bases can be used. From a desirability and usability point of view, precedents have been found to represent a familiar and natural way for design professionals to acquire and exchange knowledge. I suggest that combined with on-line technology, case-based reasoning has an even greater potential to provide access-on-demand with an intelligent computer retrieval tool leading the way to expertise being distributed in case-bases around the world.

Currently, CBR systems are much better and faster than humans at classification tasks but are not as good as human designers when it comes to creativity and innovation. Based on examination of selected existing applications, my study concludes that case-based reasoning has the most potential impact as a design *aiding* tool rather than a design *generating* tool.

VIII.2.2. Knowledge Modelling

One of the difficulties in performance-based design is the tremendous scope of information potentially used to describe the relationship between the broad needs of stakeholders and capabilities of built environments. Models needed to be developed to describe these relationships. Existing knowledge modelling approaches were adapted and modified to create new frameworks (see also referring chapters).

The **Building Performance Evaluation Domain Matrix** was the first model developed in my study (Chapter II, Section 4). It offers a way to systematically represent the domain of strategic building performance evaluation.

Each intersection on the matrix represents the evaluation of an issue – a human system level [HSL] demand *requirement* and building system level [BSL] supply *element*, viewed at a particular architectural *scale* level [ASL]. As my study shows, the matrix is helpful as a framework for visualizing and organizing the different facets of performance relationships for the purposes of research. A portion of the matrix relating to workplace comfort, defines the scope of the present study — the intersection of [HSL] individual requirements, and [BSL] building environmental service system elements at the [ASL] workplace level.

The **requirement-element performance path** knowledge models developed in my study (Chapter IV, Section 3.2) represent in more detail, and therefore enhance the understanding of, the intersections between human requirements and building elements. The facets of human requirements and building elements relating to workplace comfort and well-being are derived from domain literature. Each is modelled hierarchically using three performance levels (group, cluster and item) that ultimately link to a performance measurement(s). The paths show how performance measurement acts as a "bridge," capable of representing both desired and actual outcomes. Based on this observation, my study determined that it may be possible to use the model to begin to trace the relationship between briefing requirements and the physical elements of buildings (cases) through the measurable performance outcomes (POE criteria). One of the advantages of this modelling approach is that it is not restricted to any single performance measure. Rather, the approach supports the representation of multiple measurements. Thus, it more accurately represents the true multi-dimensional nature of building performance evaluation.

The multi-criteria requirement-element model developed in my study (Chapter IV, Section 3.4.1.) presents a performance-path representation taken one step further. It groups "bundles" of stakeholder requirements and building performance descriptions that relate to a particular workplace comfort topic, such as lighting. This type of representation is useful in describing various levels of quality.

Through the knowledge models the complexity, and at times contradictory nature, of the knowledge used in building performance evaluation is recognized. In this research, the identification of significant performance criteria for cases was achieved through the analysis and adaptation of a several existing post occupancy performance evaluation methods. I chose features that seemed both *causal* (empirical or analytical) and *influential* (re-occurring) with regards to comfort in the workplace environment. The facets modelled are therefore indicative, but not definitive.

The resulting knowledge model describes a set of performance criteria and the underlying structure or relationship between features for workplace comfort. The models represents not the full scope, but the nature of possible performance evaluations of workplace environments.

One of the barriers was the lack of universal agreement within the literature and amongst experts consulted regarding what performance criteria adequately measures human well-being and comfort. Performance relationships described in domain literature remain largely hypothetical and require further validation. Without a common basis of performance measurement, comparability of cases from different sources becomes more difficult. The attempt to further trace and validate the entities with experts using the requirement-element knowledge representations only seemed to raise more questions than it answered. For example: What constitutes a good fit between people and their workplace environment? What are the key measures that are used? Are we measuring the right things? As Pullen and Bradley ask (2004) "what do we mean when we say "workplace performance" — is it about the performance of the physical workplace or is it about the performance of the people in the physical workplace?" (My study's models emphasize people *and* physical workplace.) From this experience, two conclusions can be made: (1) the knowledge models are very helpful in making information more tractable, and (2) there is an ongoing need for development and validation of performance criteria.

VIII.2.3. MOPS Model for Knowledge Acquisition

The present study uses the measurement of building performance as a basis for knowledge acquisition. My proposed MOPS-model of measurement consists of **M**easured, **O**bserved, **P**erceived and **S**imulated data. My "POE toolkit" (Chapter IV) offers a relatively simple and convergent approach for collecting, analyzing, and representing MOPS case data related to workplace comfort.

This part of the investigation attempts to address the questions of what is involved in the acquisition and creation of case data through POE. My "POE toolkit" and the cases created from it show that a relatively straightforward POE method can be used to collect information for useful and interesting cases.

Based on the collection of real workplace performance data using the toolkit, the following insights were made about creating cases from POE:

- **Use multi-dimensional evaluation.** Collection of MOPS data is necessary to provide a complete picture of performance. Although measured data often appears to be the most convincing, the primacy of perceived data (occupant perceptions) should always be considered.
- **Collect modest amounts of data.** It is possible to collect a lot of data without yielding any useful information. In-depth studies are good for discovering new or elaborating on poorly understood phenomena. The ability, however, to compare a small amount of key data on a lot of cases is likely to be more useful for conceptual design than one detailed case-study.
- **Balance positive and negative data.** POEs tend to point out problems more than they do good solutions. During early design stages, designers crave inspiration as well as information. Identifying what works can be as important as what does not.
- **Support multi-media representation.** In multi-dimensional POEs, a wide variety of data types need to be stored including sound, text and graphics. For the communication of performance, actual acoustic samples and visual explanations of technical phenomena are compact and effective.

The POE toolkit created and used in my study principally focuses on measuring the physical comfort of individuals in relation to ambient environment conditions in a workplace. It should be noted that, for some researchers, this is not the only or even the most relevant manner to evaluate workplace environment performance. BOSTI (Brill et al. 1984) and others point to *psychophysical* constructs being important aspects of human comfort in the workplace. These include such psychological and sociological issues as morale, sense of territoriality, privacy, security, way-finding, status, and communication. Other researchers, such as Duffy (2003) and Pullen and Bradley (2004), argue that the performance of workplaces is not about measuring the environment, but about measuring people's effectiveness in the environment. Additional "tools" would need to be added to the current "toolkit" to capture such performances.

While my study shows how to populate a case-base with cases initially, it also reveals that the long-term maintenance of case knowledge is potentially a serious problem. The question is not really one of *how* to do it, but rather one of *who* does it.

From an implementation point of view, creating an on-line interface to quickly and easily allow Users to add cases to a case-base can be done with currently available technology. From a feasibility point of view, until POE becomes a more established part of the architectural design process, such as through more easy-to-use and cheaper collection tools or is mandated by regulation or standard (e.g. ISO 9000 certification), it is still uncertain whether most architect-users would be able to maintain the expertise in the system themselves. The experience of trying to acquire POE information collected by other professional consultants suggests that issues such as client confidentiality, liability, ownership, and more recently, security, may get in the way of sharing POE knowledge broadly within the building design domain. When compared to other professions such as medicine or law, architecture appears not to have developed a culture of, and therefore the mechanisms for, knowledge acquisition and sharing.

The present study concludes that relying on any one person or organization to maintain knowledge in CBR system is an unsustainable approach. Yet, a case-base that is not constantly maintained with new knowledge is likely to become quickly outdated. To be successful, the question of long-term knowledge acquisition from the domain will need to be addressed.

VIII.2.4. Case Retrieval

In addition to containing knowledge in the form of cases, case-based systems also contain knowledge about how and when to retrieve cases from their case-base. This part of a case-based system can be referred to as the Case Retriever or Case Retrieval system. My investigation shows how a performance-based approach might be used by a retrieval system to recall workplace environment cases relevant to new workplace design briefs.

In my study, a basic strategy for case retrieval is presented: (1) translate stakeholder requirements into desired technical targets, and then (2) calculate the similarity between the technical targets and the actual technical outcomes of cases in its case base. Assuming the best fit is a case where the target and actual outcomes are similar, the Case Retrieval system ranks and returns a list of its cases from "best" to "worst."

The strategy of converting stakeholder requirements is potentially a very useful part of the CBR-tool, but it requires adding a considerable amount of knowledge to the system. This is an important consideration, because unlike the cases, the Case Retrieval system's knowledge is imbedded or "hard-coded" into a CBR-tool. The more knowledge imbedded in a system, the more difficult it is to maintain potentially.

My investigation also showed that, compared to other CBR systems, a number of variations of similarity calculations may be needed because technical targets are not always discreet values. Sometimes performance targets in indoor environment design are expressed as acceptable ranges (e.g. 500-800 lux) for which a good match may be at one end or another of the range. Weighting strategies are also required to deal with situations where the Case Retrieval system must give one type of performance precedence over others.

While the Case Retrieval system's performance-based method suggested in my study is promising and adds intelligence to the search, it is concluded that there may be better, more efficient approaches. The strong desire by expert users during testing of the WEDA-demo to by-pass the Case Retriever's automatically generated targets and enter their own search terms further suggests that an alternative, more dynamically-generated indexing of the cases is needed. The technology around search engines and data-mining is evolving at an astonishing pace. Currently, two of the top five most widely used English language sites on the World Wide Web today, Yahoo.com and Google.com, are ones that offer powerful search tools that enable Web users to locate and access desired information from amongst billions of Web pages (Alexa, 2004). These search engines currenly are heavily reliant on text-matching, but this is likely to change in the future. Though outside the scope of the present study, the strategy of *emergent self-organizing technology* used on the Web to track tastes and interests based on on-line activity and user-rankings (Johnson 2001) could be used to push a system like WEDA naturally towards a state with no single individual being in control. In this way users might dynamically build up an index of cases through their own behaviour or case-rankings by others, rather than relying only on the performance targets prescribed by the system itself.

VIII.2.5. WEDA-demo

The prototype CBDA system Workplace Environment Design Assistant or WEDA-demo developed in this research represents the first application of CBR to support specifically the conceptual design of workplace environments. The significance of WEDA-demo lies not it is commercial viability, but how it is a vehicle for communicating and testing conceptual ideas.

The process used in my study of developing and testing WEDA-demo was extremely effective for assessing implementation and feasibility concerns of a CBDA system. WEDA-demo was particularly good at communicating conceptual ideas to potential end-users. This experience confirms Kelly's (2000) assertion the one should "build to learn" because while a picture is worth a thousand words, "a prototype is worth a thousand pictures" (p. 112). Through the WEDA-demo I was able to test and validate both my underlying knowledge models and overall approach with end-users. The focus-group testing also determined new features for future development such as: additional visual explanations of technical information, the ability to compare cases, and the possibility to adjust and play with the case designs.

In terms of implementation, all of the technical requirements of WEDA can be addressed with presently available technology. In terms of user acceptance, findings from the focus-group testing determined WEDA's capabilities are both desired by and would be useful to end-users. Based on this initial testing, it is hypothesized that a fully implemented on-line version of WEDA would help improve the acquisition and assessment of technical knowledge to support decision-making during the conceptual design stage of workplace environments.

WEDA-demo is prototype and not a working CBDA system. Although a KBS implementation process was used as the vehicle for this research, it was never the goal of this doctoral study to create a commercially viable CBDA-tool, or even to contribute to the development of CBR techniques. WEDA-demo's primary function, which it does well, is to provide a vision of the system to design professionals in order to test its conceptual feasibility as a decision-support tool.

VIII.3. Contribution and Application

The major accomplishments of this doctoral research are twofold: (1) the successful development of a performance-based analysis framework for evaluating existing workplace environment system elements in relation to human requirements, and (2) demonstrating how that framework might be implemented in an internet-accessible Case-Based Design Aiding tool.

The first accomplishment provides a way to understand better the nature of building performance evaluation and its role in knowledge acquisition and application. At a fundamental level, performance-based language and logic allows the design professional to transcend the prescriptive and technical descriptions of what a workplace design *is*, and begin to think of it more strategically, by what it *does*. Based on this observation, I suggest that performance evaluation therefore becomes a basis for knowledge acquisition. Its measures provide a basis for understanding the relationship between requirements and building elements. Performance paths trace the journey between that which is *desired* and that which is *provided*. In this way, the models provide a means of bridging the gap between old and new design cycles.

Associating performance outcomes with new stakeholder demands introduces a way of assessing the technical consequences of early design decisions. By ensuring that post occupancy evaluation of existing and innovative building systems translates into performance potential, the cases gain strategic value.

The implementation of the knowledge framework in a decision-making support tool in my study shows how content and technology go hand in hand. By creating cases from POEs, I am able to provide a convenient and understandable source of technical *performance knowledge*. By using CBR technology to store and recall cases when they are needed, I have created a *tool* to deliver the knowledge into the design environment. Without one or the other, the knowledge is valueless; combine the two and a strategy for supporting early design decision-making that actually works begins to emerge.

VIII.4. Future Research Directions

WEDA's conceptual model represents a unique approach for supporting early strategic design decision-making developed from performance-based design theory and case-based reasoning technology. For the purposes of transferring technical knowledge from previous design cycles into new ones, the approach appears to be both feasible and useful. The success of WEDA-demo during focus group testing and the interest that my research has received at presentations in Europe and North America suggests that the desire for a fully-implemented version of WEDA is quite strong. Before real decisions could be supported, however, the content of the current knowledge models and case library would need to be elaborated and ability of the technical targets to predict the suitability of indoor environments validated further. The prototype WEDA demonstrates the conceptual feasibility of the approach, and represents an initial step along the formulation of approaches to support the acquisition and dissemination of technical performance in early design.

Some potential avenues for future research might include:

- **Develop Cost-benefit Analysis.** Physical design or systems innovation in office design inevitably need to be related to organizational and business goals. The decision to invest in higher quality design solutions is often limited by cost, possibly without due consideration or understanding of potential long-term benefits. How can the performance evaluation of workplace environment cases be extended to include an economic model that encompasses cost and benefit factors?

- **Add new measures of performance**. In addition to the validation of existing measures, there are many other facets of workplace performance to be explored. For example, what are key programming demands and (strategic) design decisions related to new flexible ways of working given changing technology and increasing asynchronicity of work? What new building system elements and technologies allow for increased levels of personal control or environmental sustainability? Duffy observes that "the easiest things to measure are [often] the least important" (2003). While it has been relatively straightforward to measure the physical aspects of workplace environments, developing techniques to measure how well people or teams work in an environment, or determine value or spatial meaning is much more complicated, but potentially very significant to the strategic value of a workplace design solution.

- **Add new cases.** A case-based system needs to be constantly updated with new knowledge. Developing POE tools for capturing case data more easily and cheaply — so that more people can update system knowledge — will help build up case knowledge and expertise. Universal standardization of evaluation criteria will allow for comparable analysis. An on-line facility could be built to make inputting case data easier. Yet the question of who will input the cases remains largely unanswered. Can the emergent experiences and knowledge networks of the web provide the answer? How can case-base content be locally generated with a common set of tools, but collectively result in a huge resource shared world-wide? What ethical, legal, and motivational issues affect soliciting and sharing project case data within the building domain industry?

- **Add fundamental cases.** An interesting strategy to be explored is the addition of sets of cases to teach fundamental ideas, as in explanation-based learning. Explanation-based learning theory is based on findings in psychology that suggesting people use prior knowledge to guide and facilitate learning processes (Pazzani, 1994). Could design training cases establish the background from which to learn new things, laying the groundwork to infer higher level solutions from actual design cases?

- **Add new ways of searching.** How can emerging web-based self-organizing, user-behaviour search strategies be integrated in a CBR Agent, thus allowing it to become more "intelligent" through use? Furthermore, current search engines are text-based. Can new technologies that are capable of finding matches involving graphical data be developed?

- **Integrate with other tools.** WEDA was conceived as a module in a larger decision-aiding system that has yet to be developed. How could WEDA's case-based approach be combined or integrated with other existing design tools? Could WEDA's cases provide a starting set of temporary design parameters for an architect to explore and evaluate with evaluation and simulation tools that require more detailed spatial and technical information than is usually available in conceptual designs?

Through future studies, it is hoped that researchers will continue this work towards improving the fit between people and built environments, and encourage the sharing and growth of knowledge with performance-based design methods and intelligent computer technology.

APPENDIX A

Technical Targets

Technical targets this study models are derived from analysis of existing POE tools. Appendix A provides additional background and considerations regarding measurable physical performance criteria for workplace comfort.

A.1. Physical Performance Indicators

The physical performance measures (technical targets) used in this doctoral study are indicated in Figure A.1. During the POEs of case studies the measures shown with a grey background were recorded in spot measures using equipment, the non-grey were captured using occupant questionnaires and/or calculaiton. (See also Chapter VI — *Knowledge Acquisition* and Appendix B — *POE Tools*.)

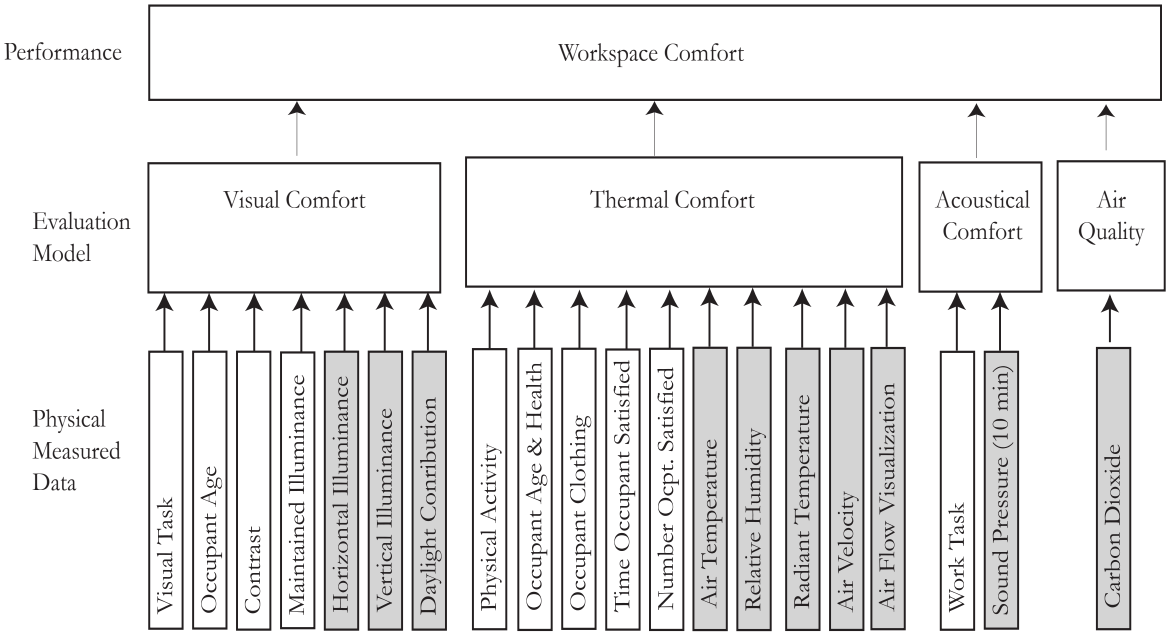


Figure A.1. Technical Targets for Workplace Comfort

A.1.1. Thermal Comfort

According to (ISO 6242-1, 1992) an preferable environment that not only prevents occupants from the extremes of hot or cold, but also provides suitable level of comfort. Factors that influence meeting these objectives have to do with:

- activity level (metabolic rate)
- age and health of occupants (adjusted metabolic rates)
- clothing worn by the occupants (insulation value of clothing or clo)
- the proportion of time people need to be satisfied (90-99%)
- the proportion of people that need to be satisfied (PMV)
- the ability of occupants to locally control their environment.

Temperature and humidity target levels in this study are based on CEN 7730 (1994) and (ASHRAE 55, 1992). The temperature range for comfort is different for summer (20-23.5 °C at 60% relative humidity) and winter (22-26°C). Using the spot measure method it is not possible to assess other temperature-related issues such as: cycling, drifts, ramps or non-uniformity.

Termparature. Three main factors influence the evaluation of air temperature: metabolic rate (activity level), air speed, and clothing. Office work is mainly sedentary, therefore people have more or less the same metabolic rate (with adjustments for age and disability). Sometimes the maximum temperature is allowed to be slightly higher (+3°C) if the air speed is also higher (up to 0.8 m/s). In such cases, occupants require direct control of air speed or its direction. It is also possible to reduce the minimum temperature based upon what people wear.

In their 1994 study, Gan and Croome (1994) postulate that people who were the usual residents in an office were more tolerant of vertical temperature differences (e.g. different temperatures at head and foot levels) (p.789). This tolerance level is important when we consider the idea of flexi-working when people are expected to work at different places, and hence may be less tolerant of temperature problems. Evaluators may want to be stricter with temperature targets in new office concept workplaces.

Humidity. Humidity, can cause dry skin, eye irritation, respiratory problems, microbial growth and other moisture-related phenomena (ASHRAE 55, 1992) (p.7). Generally speaking, the higher RH%, the lower the maximum comfortable temperature will be. This is because high air humidity reduces the ability of the human body to lose heat through evaporation from skin and by respiration. Acceptable temperatures and levels of humidity are expressed in terms of "comfort zone." (See also (ASHRAE 55, 1992)).

Clothing. The clothing people wear is primarily determined by the season and weather conditions. In office situations certain cultural or customary dress is sometimes required, such as a business suit, regardless of the outdoor conditions. The insulation value of clothing effects the amount of heat loss by a person's skin. This can both prevent a person from feeling too cold, but also can cause a person to feel overheated if the temperature around them is too high. Standards assume a certain level of clothing when suggesting targets for temperature. The "clo" unit (thermal insulation of garments) is used to adjust allowable temperature ranges (-0.6 °C per each additional 0.1 clo). Once it gets particularly cold, however, clothing has less of an impact. ASHRAE 55 (1992) states that an office worker should work in temperatures of no less than 18°C for more than an hour (p.6).

Draughts. Sedentary persons are particularly sensitive to draughts, especially where their skin is exposed (head and ankles). It is important to limit draughts and to ensure air is not flowing directly from outlets onto people. Smoke tubes are used to establish the nature of the air flow in a room by making it visible. Generally airflow should be across the ceiling from an outlet and down the walls.

Air velocity can also be indicated by how fast the smoke appears to be moving. Evaluators can use this initial test to see if there may be a velocity problem (that it is too high) before doing more accurate measures with an anemometer. It should also be noted that rooms with stagnant air can also lead to discomfort in the form of stuffiness and build up of odours.

A.1.2. Visual Comfort

> *"The characteristics most important for comfort and good visual performance are a suitable level of illumination, fairly uniform brightness for all objects in the visual field, the absence of rapidly changing light levels and avoidance of glare. The optimum level and quality of light depend to some extent on the nature of the task and the vision capacity of the individual" (Aronoff & Kaplan, 1995) p. 262.*

Horizontal illuminance measurements provide an indication of if enough light is reaching horizontal work surfaces as well as the distribution of light across the entire work area. Aronoff and Kaplan state (1995) the work surface (center of the visual field) should have an even distribution of light (less than 3:1 brightness contrast) and within the field of view of the task (approximately 1.5 m) the contrast should be less than 10:1. Surfaces should be matte with reflectance not exceeding 30%. Keep in mind, the higher the contrasts present (i.e. between windows and walls) the higher the lighting level needs to be.

Vertical illuminance measures can provide an indication of glare as well as whether or not enough light is reaching the faces of employees (important greeting, conversing). Again, avoid sharp contrasts between horizontal and vertical surfaces.

Taking measures with the lights on and off provide an indication of the daylight contribution. Although electric lighting is the main source of illumination in workplaces, daylighting is considered to provide an important aesthetic and psychological benefit (view, eye relaxation). It also offers energy savings. Daylighting is obviously not effective for use in deep buildings.

Table A.1. NEN 1890/3087 Lighting Level Recommendations

Class	Light Strength	Type lighting	Subclass		
Class I	10-200 lux	Orientation lighting			
Class II	200 – 800 lux	Work lighting	A	200 lux	Rough details
			B	400 lux	Reading, writing; similar detail and contrasts
			C	800 lux	Small details; high contrasts
Class III	800 – 3000 lux	Special lighting			

The lighting levels required for VDT use (300-500 lux) are slightly less than those for paper-based tasks (reading, writing) (500-800 lux). Where both tasks occur, task lighting is often recommended to supplement the lower ambient lighting levels for VDT use. Light sources (i.e. the flourescent tube) should not be visible in occupant's field of view and overhead sources should be shielded (Aronoff et al., 1995).

It is interesting to observe that in their 1995 study, (Begemann, Beld, & Tenner, 1995) noted that, when given a choice, people did not change the lighting level according to task (VDU, writing, talking), but by location – choosing to have 25% lower lighting levels at a conference table compared to their desk. This finding is interesting for the lighting design of newer flexible work environments where occupants are more mobile, often moving to task-specific work areas rather than remaining at a single assigned desk for the entire work day.

Referenced standards for minimum lighting-related technical targets: Dutch standards (NEN 1890, 1991) (NEN 3087, 1991) and (ISO 8995, 1989) as well as international standard (IESNA, 1993).

To take into account more than visual task, activity (detail size), contrast and age-adjusted IESNA recommendations for maintained lighting levels [E_m] (IESNA, 1993) were included in my study.

For the specification of the lamps and luminaires a more comprehensive evaluation such as (CEN:prEN 12464, 1998) can be used that includes activity-based targets for maintained illuminance [E_m], Unified Glare Rating (upper) limit [UGR_L] for the artificial lighting, and Colour Rendering Index [R_a]).

Judging by the optimum range is different than that of the minimum range suggested that standards use. Begemann (1995) argues that today's standards for meeting visual needs in office rooms are significantly lower than the needs required for optimal biological stimulation of human beings. In other words, forcing people to work under 500 lux during the day is biologically too dark.

A biological stimulation effect (related to time of day) is "alertness," an obvious component in performance. If we relate this to lighting then there is an argument for installations that more closely represent natural daylight effects by providing higher lux levels. Circadian rhythms, or the body's natural timeclock for sleeping and wakefulness, takes its cues from the environment around it. People living in northern countries (e.g., Scandinavia, Canada) report a syndrome related to depression and lower productivity, known as SADD, is thought to be related to the reduced exposure to daylight during the winter months. The close relationship between lighting level an health in (Begemann & Beld, 1998) estimates that the additional energy costs for increasing levels of lighting are marginal when compared to the amount represented by a 1% gain in productivity from improved lighting levels (p. 25).

In qualitative studies done in Northern Europe the highest satisfaction levels for all types of workplaces was approximately 1000-2000 lux (Kluwer Techniek, 1999) p. 22). The maximum amount was around 5000 lux. This led the researchers in the Kluwer study to the conclusion that 1000-2000 lux is the best range considering energy use, cost and occupant satisfaction. For my own study, based on NEN standards, optimal ranges were much lower (300-800 lux), but future researchers may want to consider the importance of lighting (and absense of lighting) on human productivity and performance revealled in circadian research.

A.1.3. Air Quality

Humans produce carbon dioxide (CO_2) proportional to their metabolic rate. It is the largest human bioeffluent. In itself, CO_2 is considered harmless, but unlike other types of pollutants is relatively cheap and easy to measure. It is used as an indicator of other bioeffluents that are perceived as a nuicence, the ventilation rate, and the proportion of outdoor air blended with the recirculated air. It has also been used to provide an indication of percieved indoor air quality. CO_2 monitoring only applies to places where people (sources of bioeffluents) are present, and does not account for hazardous air pollutants such as carbon monoxide and radon.

The difference between outdoor concentration and indoor concentration is used to determine the CO_2 generated in a space. Outside CO_2 concentrations are around 350-400 ppm. Acceptable levels for CO_2 in offices are referred to either as the indoor concentration minus to the exterior value or in absolute or total room values as in (ASHRAE 62, 1989) and (ISO/DIS 9241-6, 1998).

Concentration levels as high as 10 000 ppm have shown no significant health effects. For normal occupancy conditions, however, CO_2 concentrations above 1000 ppm are an indication of inadequate ventilation for comfort and may mean that the ventilation rate is inadequate for diluting other, more harmful pollutants (Liddament, 1997) p.32. Studies also relate CO_2 concentrations with the percentage of people visiting a space who are dissatisfied with the level of odour (ppd). Typically, 20% ppd corresponds to 650 ppm above the odour value or 1000 ppm actual CO_2 concentration. (Persily, 1994) in (Liddament, 1997).

The main areas of error for spot measures relate to the time it takes to reach steady-state conditions, assumptions about the rate of CO_2 generation, and fluctuations in outdoor concentrations. Timing of air quality measures is especially critical. Ventilation rates and temperature regulation is relaxed in off hours and ramped up before occupants arrive for work. Liddament (1997) states it can take more than three hours to reach steady state conditions with air change rates less than 3 per hour. Depending on the way the building is operated the concentration of contaminates can be much higher during the morning. Air quality is also seasonally affected where exterior air mix is reduced in winter. If you are looking for worst case – pick a bad exterior climate day. If you are looking for an average day – data can be collected under less stringent conditions.

A.1.4. Acoustical Comfort

The reference standard used is (CEN:prENV 1752, 1997). The evaluation of: L_{eq} established by the CBO-TNO expert consulted as part of this study. Common sources of noise are equipment (computers, air-handling), outside traffic, and between spaces. Most annoying and disturbing noise carries information, such as colleagues talking. Measuring the level of speech intelligibility rather than, or in addition to, noise level is particularly meaningful for the acoustic comfort of workplace environments. Though not available for use in this study, emerging techniques for spot measuring speech intelligibility should be included in future studies.

Extremely quiet spaces just as bad sometimes as noisier ones – general sound is good because it can mask sound. Single bits of intelligibility information are harder to pick out. This is why landscape offices generally are allowed higher ratings than enclosed offices.

APPENDIX B

POE Collection Tools

Exemplars of protocols, worksheets and questionnaires used in this study to collect Measured, Observed and Perceived case information.

B.1. Measured Performance

Table B.1. Physical Measures Protocol

Measure	
Air Temperature (t_a) [°C]	**Aspect:** Thermal comfort (heat transfer by convection) **Position:** At 1.1 m height at workplace in the middle of the room **Measurement time:** 3 minutes. **Notes:** Before readings are made, equipment should be placed/be present in room for at least 10 minutes to acclimatize. The sensor should not be placed in direct sunlight or close to radiating sources (like radiator, pc's) or in the plume of warm air coming from equipment like pc and printer nor in the supply air flows.
Relative Humidity [%RH]	**Aspect:** Thermal Comfort (heat loss by evaporation) **Position:** At 1.1 m height at workplace, in the middle of the room **Measurement time:** 3 minutes **Notes:** Before readings are made, equipment should be placed/be present in room for at least 10 minutes to acclimatise. The sensor should not be placed in direct sunlight or close to radiative sources (like radiator, pc's) or in the plume of warm air coming from equipment like pc and printer nor in the supply air flows.
Carbon Dioxide (CO_2) [PPM]	**Aspect:** Air Quality (bio-effluents) **Position:** In the middle of the room. **Measurement time:** 3 minutes or minimum time required by equipment **Notes:** Sensor should not be placed in the direct neighborhood of persons (less than 1 m) because off high CO_{2}- concentration in expired air. Measurements preferably to be carried out (just) before lunch break.
Illuminance on a horizontal plane [LUX]	**Aspect:** Visual Comfort **Position:** At desk within 2.5 m, 2.5-5 m, & >5 m from façade. **Measurement time:** With lighting on and lighting off **Notes:** Do not place the sensor where the people or other objects in the room may cast a shadow onto it.
Illuminance on a vertical plane [LUX]	**Aspect:** Visual Comfort **Position:** At VDU, chair of employee, & locations mentioned above **Notes:** Do not place the sensor where people or other objects in the room may cast a shadow onto it.
A-weighted equivalent sound pressure level (L_{eq}) [dB(A)]	**Aspect:** Acoustics **Position:** At a height of 1,1 m above floor, in the middle of the room. **Measurement time:** 5 minutes **Notes:** Use a tripod – do not rest instrument on desk. Take notes of the type and source of sounds occurring during the measurement period (talking, telephones, cars in street...)
Air flow Visualisation (sketches & notes)	**Aspect:** Thermal comfort **Position:** From supply air grills and/or down draught from windows **Notes:** Document the air flow pattern with notes and/or sketches. Look for draughts or flows that go directly onto people.

Insulation value of clothing [I_{cl}] *or* [clo]	**Aspect:** Thermal comfort (heat by radiation & convection or loss by evaopration) **Measurement time:** Mean over ½-1 hr. period Prior to taking physical measures, note the type of clothing worn by persons in the workspace. Calculate clo by adding up insulative values of clothing ensemble **OR** use estimation method (see Table B.2. below)
Photography	From center of room or two positions (for larger rooms) Take 1 picture every 1.5° for 360 degrees Position camera vertically on tripod. If possible, do not use flash (or use a diffuser). Adjust exposure (over expose) when shooting towards windows. With a non-digital camera try F8 and meter for shutter speed on wall near floor.

Table B.2. Additional Physical Measures

Measure	
Ventilation [l/sec/m²]	**Aspect:** Thermal comfort **Position:** At inlet **Time:**1 minute **Notes:** A zero pressuring measuring device (e.g. Acin Flowfinder; ±5%) is calibrated on site once device is in place. Reversing the device can measure air volume going out as well. Ventilation Rate (air changes per hour) can be calculated based on this measure. Typical rates are 2-3 changes per hour, 8 changes is considered to be very high.
Maximum Mean Air Velocity (v_a) [m/sec]	**Aspect:** Thermal Comfort(heat by convection or loss by evaporation) **Position:** At ankle height (0.133m), abdomen height (0.75 m) sitting neck height (1.1. m) standing neck height (1.7 m) Based on equipment. Hot sphere: **Time:** ½ hour with a measure every second, or 3 minute with 10 measures per second (1800 data points) **Notes:** Using a mechanical or thermal amenometer. Record air movement in the direction of the workstation. The Dantec is a hot sphere anenometer is calibrated in the lab (10% accuracy in low, under 0.5 m/s, air velocities). The data is recorded into a portable computer or logger.
Thermal Radiation [E_{eff}] or Mean Radiant Temperature [t_r]	**Aspect:** Thermal Comfort (heat by radiation) **Position:** Surfaces in room **Time:**1 minute **Notes:** Using a thermal resistance device (e.g. PT100[a]) taped to surface. Black globe thermometers are used for mean radiant temperatures[b]. For the Looking for excessive differences in radiation between vertical surfaces and floor, floor to ceiling.

[a] PT100 stands for "Platinum 100 Ohm resistance." The resistance of the material changes depending on its temperature. By measuring the resistance of an electrical signal sent through the device a polynomial calculation is used to determine the temperature value. This can be done manually (look-up table) or automatically by data logger with built-in calculator (± 0.1°C)

[b]Globe temperatures are not recommended in comfort measures (ISO 7726, 1985)

Table B.3. Estimation of CLO;

	Male	Female
Summer	0.7	0.5
Winter	1.0	0.85

Source: (Groot, 1996)

Table B.4. Estimation of Metabolic Activity

Work	Metabolic Rate [M/m3]
Rest	50
Sit	60 ± 5
Low Level Activity	100 ± 7.5
Moderate Activity	165 ± 10
High Level Activity	230 ± 15
Very High Level Activity	290

Source: (Groot, 1996)

B.2. Observed Performance Log Sheets

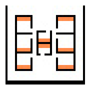
The following pages provide examplars of the collection sheets developed for undertaking observation studies. During observation studies the workplace is surveyed with or without the help of the in-house facilities staff. Materials required are log sheets (see following exemplars) and floorplans of the areas being observed. Observations are made unobtrusively without talking to the occupants. Observation is done in stages: (1) validate floorplan (2) use worksheet to survey physical and sensory features and make notes (3) walk through area and make notes about personal experience of workplace (4) make observations about the behaviour of people. During analysis, check for similarities and differences in the data collected from observation study with perceptions of the users (questionnaires and interviews).

Some of the open areas on the log sheets are for the recorder to make longer descriptions of observed occupant behaviours and modifications. Stress behaviours and modifications are a good indication that there is a problem with the workplace environment. According to Smith & Kearny (1994) this includes adaptations (e.g. obscuring a vent or window with a sheet of paper), low energy (e.g. errors, working slowly), avoidance (e.g. absence, visiting, wandering), poor communication or irritation (e.g. complaining, anger), and pain (e.g. headache, backache, nausea. Individuals also differ in their ability to screen out unwanted stimuli – *low screeners* are particularly susceptible to being distracted, losing concentration and having to start tasks over (ibid. p. 178). Keeping detailed notes helps to clarify the nature of the occupants, their tasks, and their actions.

APPENDIX C

WEDA Case Example

Complete contents of Case L used in the WEDA-demo that shows the extent and multi-media diversity of attributes-values.

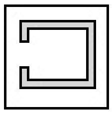
CASE_ID	**TUE HG 10.73**
Building Level	
Building_Type	Office
Building_Image	<picture of Main Bldg.>
Building_Country	NL
Building_Site_City	Eindhoven
Building_obstruction	None
Building_depth_type	Shallow depth
Features_Façade?	None
Floor Level (Setting)	
Client_name	Faculty of Architecture, TU/e
Client_Function	TUE & CBO building physics research offices
Sample_plan_area	454.1 m2 (not incl. laboratoria)
Total_population	15
Overall_density	16-30m2 per person
Percent_circulation	20%
Percent_support	5%
Percent_cellular	60%
Percent_open_plan	15%
Consultants	unknown
Workplace_ layout_type	 cell or high partition
Workstations_≤7m_ from_Window	80-100%
Work Space Brief	
Work_pattern_type	Cell (concentrated study, isolated work, low interaction high autonomy, laptop/ networked PC, individual timetabling)
Worker_type	Independent
Average_Age	40-55
Number_workstations	1
Code_Luminance_ ratio	10:3:1 (NEN 1890) (task-surrounding-periphery)
Code_Illuminance	400-800 lux (NEN 1890)
Code_Lighting_ Energy	<1.9 (NL Energy Performance Norm)

Visual_Task_ Background	Light
Visual_Task_ Importance	Important
Use_of_Daylight	Maximum
Importance_view	Important
Interior_wall_colour	Light
Interior_ceiling_colour	Light
Interior_floor_colour	Medium
Colour_rendering	Natural colours
Lighting_colour	Warm white
Light_direction	Indirect/direct
Energy_efficiency	Ideal

Work Space Solution (Stuff)

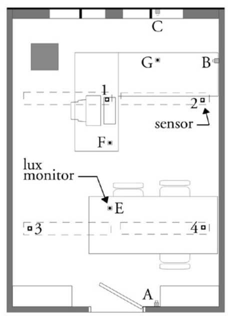
Space_type — enclosed

Plan_layout



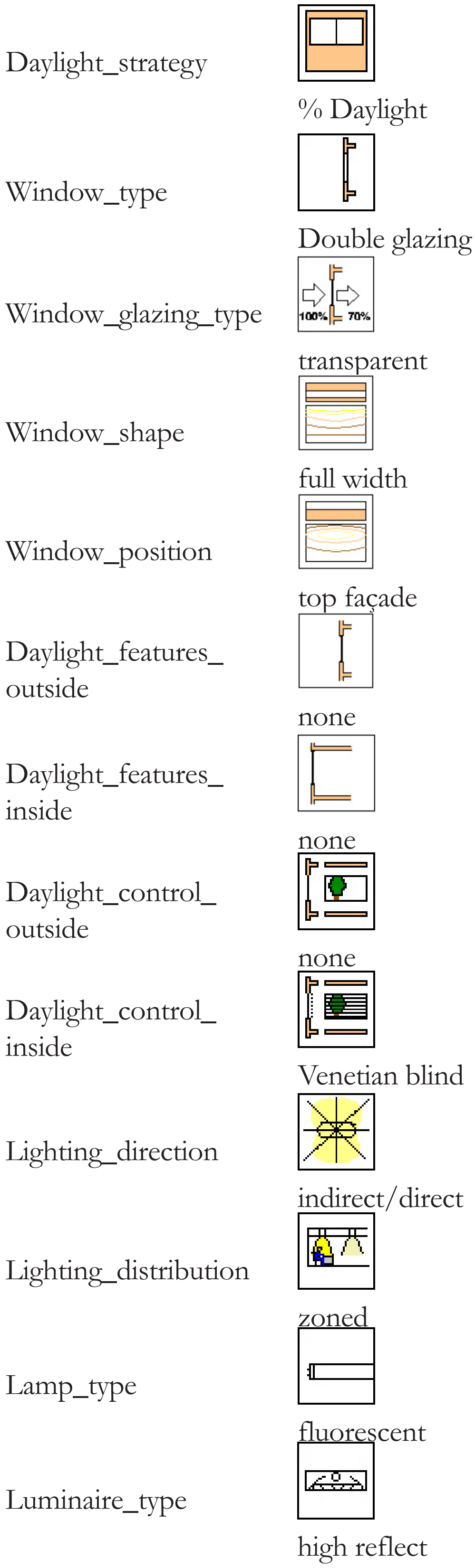
ulilateral

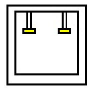
Plan_view



<CAD dwg>

Internal_height	2580 mm
Internal_depth	4930 mm
Internal_width	3600 mm
Distance_from_ window	<5 m
Window_orientation	west
Window_glazing_area	51-75%


Daylight_strategy
% Daylight
Window_type
Double glazing
Window_glazing_type
100%
70%
transparent
Window_shape
full width
Window_position
top façade
Daylight_features_ outside
none
Daylight_features_ inside
none
Daylight_control_ outside
none
Daylight_control_ inside
Venetian blind
Lighting_direction
indirect/direct
Lighting_distribution
zoned
Lamp_type
fluorescent
Luminaire_type
high reflect

Luminaire_position	 pendent
Task_lighting	None
Daylight_control_ automation	Auto local
Artificial_lighting_ control_ position	Local
Artificial_lighting_ control_ automation	Auto – light sensor
Artificial_lighting_ control_ switch	Dimmer (continuous)
Relamping	Spot replacement
Lighting_system_story	T5 lamps were chosen because they are highly energy efficient. They are expensive so initial costs are higher.

Measured Outcome

Sample_temp_winter	23.2 C
Sound_pressure_level	33.8 Leq
Problem_Sound_ sample	<.wav file>
Illumination_level	200-500 LUX
Reflection_factor_ floor	20-30%
Relection_factor_walls	60-70%
Reflection_factor_ ceiling	70-80%
Lamp_colour_ temperature	2900-3300 °K
Rendering_Factor	80-90% Ra
Lighting_power_ consumption	<1.9 EPN
View_distance	>5m

Observed Outcome

Panorama	<picture>
Daylight_contribution	High
Visual_defects	None

Disability_glare	None
Discomfort_glare	None
VDU_Veiling_reflection	None
View_quality	High
Ease_of_relocating_lights	Difficult
Observer_lighting_story	Lighting system is highly responsive to daylight, adjusting artificial lights automatically to maintain a constant pre-set level of 500 lux.

Perceived Outcome

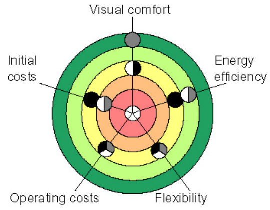
Productivity	+10%
Overall_Comfort	Good
Achieve_desired_conditions	Very Quickly
Glare_Sun_Sky	Occasionally
Glare_artificial_light	None
Control_over_glare	Full control
Lighting_satisfaction	Very satisfactory
Quality_view_outside	Good

Simulated Outcome

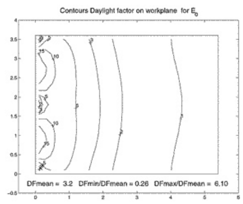
Predicted_Percentage_Dissatified

<no value>

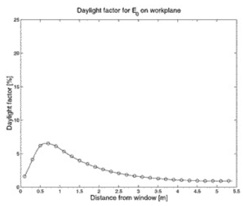
ILSA_performance_chart



Daylight_factor_distribution_section

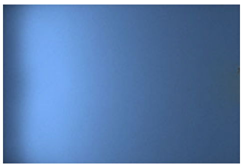


Daylight_factor_distribution_plan

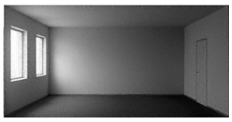


Side_wall_rendering

Plan_rendering

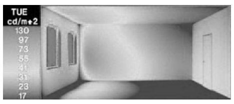


Cross_section_rendering



Perspective_rendering

False_colour_image



Detailed_rendering

APPENDIX D

WEDA Evaluation Workshop

Table D.1. WEDA Workshop Agenda

9:30 AM	Introduction/ Welcome Introduction (SMH) and overview of day's objectives
9:40 AM	Presentation Overview of Prototype Development
10:00 AM	Self - Introduction Facilitators and Participants
10:20 AM	Reactions to WEDA Retrieval (Group Outliner) Demo + Input from participants
11:00 AM	Coffee/Tea Break
11:15 AM	Suggest improvements (Group Outliner)
11:30 AM	Select the most important improvements to make (Vote)
11:35 AM	Reactions to WEDA Browser (Group Outliner) Demo + input from participants
11:55 AM	Which modifications are the most important (Vote)
12:10 PM	Summary

The session began with a welcome and overview of the objectives and agenda for the meeting. This was followed by a presentation on the development of the WEDA prototype and an introduction to the use of Group Decision Support System software. Participants were invited to begin using the group decision software by introducing themselves electronically.

The first task for participants was to evaluate WEDA's retrieval environment. After being shown a demonstration of WEDA retrieving cases, participants were asked to comment on a list of specific concepts (or strategies) that define the way WEDA retrieves cases (see Table D.2.). The desired outcome of this task was to validate the approach taken to create WEDA by generating a list of potential risks, benefits, and key issues.

Table D.2. Evaluation of Retrieval Strategies

Please make your comments on the following strategies used in WEDA's Retrieval Environment	
1. Translate brief to technical targets automatically	Advantages Disadvantages Other comments
2. Use technical targets to locate cases	Advantages Disadvantages Other comments
3. Use multiple technical targets to describe performance	Advantages Disadvantages Other comments
4. Use a percentage and "distance" to describe level of match for multiple targets	Advantages Disadvantages Other comments
5. Case values that do not match the targets exactly or fit within ranges are 0% match	Advantages Disadvantages Other comments

After the coffee-break participants were given their second task to evaluate WEDA's browser environment. A copy of WEDA's browser was provided at each station so participants each could "play" with the software independently. WEDA's browser provides considerable user-control and data relating to design cases. Therefore, participants were asked to respond to general questions about the navigation around and content of the cases (see Table D.3.). The purpose of this activity was to have end-users validate the approach taken (is the information and the way it is presented useful for design?), and help generate a list of creative ideas for potential improvements for the system (identification of desirable features).

Table D.3. Participant's Evaluation of Browsing Environment

Please comment on WEDA's Browsing Environment	
1. General impressions	1.1 Positive 1.2. Negative 1.3 Other comments
2. Potential as a "Feed-forward" tool for connecting POE to early design	2.1 Which features should be added? 2.2 Which features are not needed? 2.3. Other comments?

As a final task, an electronic voting session was originally planned to priorize issues raised during the session. During this activity participants would be asked to review all of the comments and suggestions made during the session and then vote to priorize the issues. The purpose of this activity was to determine what would be the top 10 issues to address given the time and resources to improve WEDA further. There was not enough time, however, to complete this task during the meeting. Therefore, attendees agreed to respond to a follow-up vote by mail.

The session was concluded with a short summary of the group's results and introduction to the afternoon session.

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Acronyms

4-RE's	Retrieve, Reuse, Revise, Retain
AI	Artificial Intelligence
ANSI	American National Standards Institute
ASHRAE	American Society for Heating Refrigeration and Air conditioning Engineers
ASL	Architectural System Level
ASTM	American Society for Testing and Materials
BFIM	Bouw Fysisch Informatie Model [Building Physics Information Model]
BMS	Building Management System
BSL	Building System Level
CAD	Computer Aided Design
CBD	Case Based Design
CBDA	Case-Based Design Aid or Assistant
CBO	Centrum Bouw Onderzoek TNO-TUE [Centre for Building and Systems Research]
CBR	Case-Based Reasoning
CDM	Conceptual Data Model
CFD	Computational Fluid Dynamics
CR	Case Retriever (or Case Retrieval system)
CSP	Constraint Satisfaction Problems
DFG	Dutch Florin Guilders
ESRU	Engery Systems Research Unit (U. of Strathclyde)
FAGO	Fysische Aspecten van de Gebouwde Omgeving [Physical Aspects of the Built Environment TU/e]
FBS	Function Behaviour Structure
GDR	Group Decision Room
GDS	Group Decision Support
HSL	Human System Level
HVAC	Heating Ventilation and Air Conditioning
IBPE	International Building Performance Evaluation
ICF	International Centre for Facilities
IEA	International Engergy Agency
IESNA	Illuminating Engineering Society of America
ILSA	Integrated Lighting System Assistant
ISO	International Organization of Standardization
ISSO	Instituut voor Studie en Stimulering van Onderzoek op het gebied van gebousintallaties

	[Institute for the study and promotion of research in the feld of building services]
KBS	Knowledge Based System
LBNL	Lawrence Berkely National Laboratory
MBR	Model Based Reasoning
MOP	Memory Organization Pattern (Schank, 1982)
MOPS	Measured Observed Perceived Simulated (POE performance measures)
NEN	Nederlands Normalisatie-instituut [The Nethlerlands Standardization Institute]
PAM	Performance Assessment Method (Clark et al., 1996)
PEST	Political Economic Sociological and Technological
POE	Post Occupancy Evaluation
PROBE	Post-occupancy Review of Buildings and their Engineering (UBT, 2004)
SBPPE	Strategic Building Performance Planning and Evaluation
SBS	Sick Building Syndrome
ST&M	Serviceability Tools & Methods® (ICF)
TEMA	Technical Management (Department of)
TNO	Toegepast Natuurwetenschappelijk Onderzoek [Netherlands organization for Applied Scientific Research]
TQM	Total Quality Management
TU/e	Technische Universiteit Eindhoven [Eindhoven University of Technology]
TUS	Time Utilization Study (Duffy, 2003)
VDU	Video Display Unit,
VDT	Video Display Terminal
WEDA	Workplace Environment Design Assistant
CSD	Case Studies Database (from (Papamichael, LaPorta, & Chauvet, 1997)
BDA	Building Design Advisor (Papamichael et al., 1997)

Nomenclature

The following are explanations of symbols and formats; these are the definitions used in the study and may be more restricted than in general use. Metric or S.I. Units are not explained.

%RH	Percent Relative Humidity
°C	Degrees Celcius
.DXF	Drawing Exchange Format (image file format)
.FPX	Flash Pix (image file format)
.JPG	Joint Photographic (Experts) Group (image file format)
.WAV	Wave table synthesis (audio file format)
$C0_2$	Carbon dioxide concentration [ppm]
dBA	DeciBles A-weighting sound pressure level
E_{eff}	Thermal radiation
$l/sec/m^2$	Volumetric flow-rate for outdoor air ventilation in litres per second per square meter
L_{eq}	A-weighted equivalent sound pressure level over 5 minutes
LUX	Unit of illumination = 1 lumen/ sq/m or .0929 ft candles
m/s	Metres per second
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
ppm	Parts Per Million
T	Temperature [°C]
t_r	Mean Radiant Temperature
v_a	Maximum air velocity [m/sec]

Glossary

Activities. Those events or behaviours taking place within a given area by a specific type of occupant.

Adaptable. Something that is capable of progressively achieving suitability with specific needs and objectives. (Aronoff & Kaplan, 1995).

Adaptable Design. Design that offers basic universal features that can easily be adjusted to the meet the needs of a specific user (Vischer & White, 1991).

Adaption Cost. Certain losses such as reduced work quality, slower pace of work and more rapid fatiguing resulting from people having to deal with chronic stress (Aronoff and Kaplan, 1995). See also *Occupational Stress*

Adaptation (see also ***Stress Behaviour***)**.** Changing natural behaviours to fit uncomfortable situations. It requires physical and psychological energy and thus reduces energy for work (Smith & Kearny 1994).

Ambient environment. The sensory properties of a given area. Vision, hearing sense of smell, and temperature are considered, among others.

Artificial Intelligence [AI] A discipline within the field of computer science concerned with building computer programs that imitate human behaviour. More specifically, programs that perform tasks that require intelligence when performed by humans (e.g. game playing, inference, learning, plan formation, speech recognition, natural language understanding). Expert systems are an application of AI.

As-built. Actual physical characteristics of an existing building, as opposed to what may be described in design or construction documents and specifications (see also ***as-designed state***).

Attribute value. A numerical quantity or text that is assigned or determined by calculation or measurement for a given attribute. Usually includes type of data (format).

Benchmarking. **"**How buildings perform on a cluster of attributes against the whole data set,"(Leaman, 1997) p. 38. "Benchmarking is the continuous process of measuring products, services and practices against the toughest competitors or those companies recognized as industry leaders" (Kearns, 1987).

Building. A physical artifact. A shelter comprising a partially or totally enclosed space erected by means of a planned process of forming and combining materials (ASTM E631-89a, p.6).

Brief (or ***Program***). A product of briefing, it is a document containing information containing client requirements for a design. Requirements can be performance-based (specifies the function the solution is required to meet) and prescriptive (specification of a product, solution or procedure which has worked well before) (Worthington, 1997).

Briefing Process (see also ***Programming***)**.** Establishes a client's needs, identifies requirements, sets out the process of procurement and establishes measures against which performance can be evaluated. It can occur during various phases of design: pre-project, project, and post project (Worthington, 1997).

Briefing, Strategic (or Scenario Briefing). An early design process for analyzing and defining building stakeholder requirements according to a range of possible futures. Distinct as defining a vision of success but not necessarily a means of achieving that success. (See also **Planning, strategic**).

Case-based reasoning [CBR]. An artificial intelligence paradigm. A problem-solving strategy where a unique problem is addressed using the same techniques used to successfully resolve previously encountered problems.

Case Based Design Aid or Assistant [CBDA]. An application of case-based reasoning that supports or stimulates creativity, learning and design-decision-making with design cases.

Case Based Design System [CBD]. An application of case-based reasoning that is capable of generating new designs by adapting or modifiying existing cases.

Case Memory. A special sort of database in which individual or multiple cases are treated as units for query (Maher, Balachandran, et al., 1995 143 /id).

Case Retriever or Case Retrieval System. Component of a case-based reasoning system that contains control knowledge that determines when and how cases are retrieved from the case library.

Change management. The analysis of change in terms of its effect on employees. Management can mitigate negative impacts of change by reducing the stressful aspects of it (resentment, anxiety) (Becker, 1990 after Rapoport, 1970).

Changeability. The ability to adapt to the changing needs of a building's inhabitants. Often the need to replace mechanical or electrical equipment in a building is not because of physical failure, but technological or functional obsolescence.

Churn. The proportion of occupants in an office who have to exchange their work places in a given period, usually a year.

Client-server model. A programming technique that links together several programs through a single source application. Control of all other applications comes from within a single application.

Combi-Office. Office layout that provides for both cellular and groups space for users.

Colour Rendering[R_a]**.** The ability of an artificial light source to make colours in the environment, of objects and of human skin to appear as natural as possible. The colour rendering index [R_a] is an objective measure of this property (the maximum of R_a is 100) (CEN:prEN 12464 1998, prEN 12464).

Computer Aided Design [CAD] (or ***Computer Aided Design and Drafting [CADD]***). A term used to describe computer programs that incorporate drawing tools to assist designers in the creation and visualization of architectural and engineering designs.

Confidence intervals. Statistical term**.** Show the mean for the particular variable and upper and lower confidence bands. (Leaman 1997) This describes the confidence (e.g. 19 times out of 20) in the true value falls within the bands a certain percentage of the time (e.g. 95%).

Criteria. The standards against which the performance of actual buildings in use is compared.

Data collection or gathering. The process by which information pertinent to a given study is obtained. Data are extracted from a variety of sources. (see also *Post Occupancy Evaluation*)

Data sheet (or **form**); a display window in a computer program designed to resemble a form with blank spaces to fill in information. It is used to query the user for input data for a database. An example of a line on the form may be: "width of room: _____ mm." This is also known as *query by example* interface.

Decision trees. A tree where each branch or node represents a decision. A leaf is outcome of a sequence of decisions taken from root to leaf. Usually binary (two alternatives at each decision point such as "yes" or "no") (Oxford, 1991). See also *tree.*

Design constraints. Limits or restrictions that effect the manner in which a design is created - that which defines the satisfaction of the design goals.

Design description. The statement of the design components that constitute the design solution (Maher, Balachandran, et al., 1995).

Design elements. Components of a design.

Design requirements. The design specifications of a design problem. They may be stated in terms of function, performance (behaviour), and physical (sturctural) characteristic (i.e. material, colour, etc.) requirements.

Digital image; see *raster image.*

Documents. All printed matter examined in a study, including institutional publications, accident reports, newspaper accounts, and so on.

Domain. The area of expertise of an expert. For example, the domain of an architect is building design.

Domain of discourse. language and terminology used within a particular domain.

Durability. The capability of a building, assemly , component, product or construction to maintain serviceability over at least a specified time. (ASTM 631-89a)

Environment. Denotes the physical attributes of a given activity area.

Environment, Indoor. See *indoor-environment*

Environmental Psychology. The emotional impact of physical stimuli and the effect of physical stimuli on a variety of behaviours such as work performance or social interaction p. 20 (Clements-Croome, Kaluarachchi, and Baizhan 1997)

Evaluation. The activity of comparing performance criteria with actual performance measures.

Evaluation; Qualitative and quantitative judgement of the value of solutions relative to the satisfaction of criteria. The source of criteria may be determined by the designer (internal) or referenced from external sources. For example comparison of existing building design to building code requirements set by governing agencies (external) or against performance criteria set by the client (internal).

Expert; "A person with extensive experiential and intuitive knowledge that is considered valuable" (Carrico, et al., 1989).

Expert system; a type of computer program designed to contain knowledge of an expert, usually narrow in scope and limited to a single specific subject domain (i.e. medical diagnosis).

Explanation facility. Part of a computer program used to provide help or additional information to the user. In some expert systems the rationale used by the computer to reach a conclusion is recorded so that the user can review it to see how the conclusion was reached.

Facilities Design. The determination of how design components of a facility support achieving the facility's objectives. Design components consist of *facility systems*, the *layout*, and the *handling system* (Tompkins et al., 1996).

Facility. Is within a building, a whole building, or a building with its site and surrounding environment; or it may be the construction that is not building. The term incorporates both the physical object and its use (ASTM E631-89a).

Facility Handling system. The mechanisms need to satisfy the required facility interactions, p. 3 (Tompkins, White, Bozer, Frazelle, Tanchoco, and Trevino 1996).

Facility layout. All equipment, machinery and furnishings within the building envelope, (Tompkins, White, Bozer, Frazelle, Tanchoco, and Trevino 1996).

Facility Management. Efforts related to planning, designing, and management of occupied buildings and their systems, equipment and furniture to enhance an organization's ability to meet its business or programmatic objectives (Becker, 1990 & 1987).

Facilities Planning. A composite of facilities location and facilities design. The objective of facilities planning is to plan a facility that achieves facilities location and design objectives.

Facility Serviceability. The capability of a facility to perform the function(s) for which it is designed, used, or required to be used (ASTM E631-89a).

Facilities Systems. The structural systems, the atmospheric systems, the enclosure systems, the lighting/lelectiral/communication systems, the life safety systems, and the sanitation systems. P. 3 (Tompkins et al., 1996)

Flexibility. The capability for low cost, rapid change. Such as rearranging a workstation. (Salustri, 1990)

Function. Denotes specific area/activity requirements for a given setting. An office setting might have the functional requirements of photocopying space, desk space, restrooms, and waiting area.

Glare. A sensation produced by bright areas within the field of view and may be experienced either as discomfort or disability glare. Glare caused by reflections in specular surfaces is usually known as veiling reflections or reflected glare. (CEN:prEN 12464 1998, prEN 12464)

Glare, disability. Glare caused by excessive luminances or contrasts and impairs the vision of objects. In interior situations it can usually can be avoided by shielding lamps or shading windows. (CEN:prEN 12464 1998, prEN 12464)

Glare, discomfort [UGR]. Glare caused by luminaries or other artificial lighting sources. (CEN:prEN 12464 1998, prEN 12464)

Human Factors (individual)**.** Aspects of the individual which influence productivity including: well-being, ability to perform, motivation, job satisfaction, technical competence. P.21 (Clements-Croome, Kaluarachchi, and Baizhan 1997)

Image. The perception of a given building or environment in terms of aesthetic quality.

Illuminance, maintained [E_m]. Value below which the average illuminance on the specified surface is not allowed to fall. (CEN:prEN 12464 1998, prEN 12464) The reference surface can be horizontal, vertical, or inclined.

Intuitive evaluation. That aspect of an evaluation not substantiated by objective data, but based on the intuitive judgement and expertise of the evaluator.

Indoor Environment. The immediate surroundings of an internal workspace (including light, sound, temperature, ventilation, indoor air quality and pollution), (Clements-Croome, Kaluarachchi, and Baizhan 1997). Sometimes referred to as indoor climate.

Intelligent Buildings. An integration of automated building control technology, advanced telecommunications, and office automation enabling the office to be operated more efficiently and to be more response to occupants' changing needs (Aronoff and Kaplan 1995) p. 126. Some "low-tech" (e.g. naturally-ventilated buildings) are also considered to be "intelligent" by virtue of their responsiveness to exterior conditions and/or effectiveness in providing support for organization and activities

Knowledge Based System. A type of computer program that uses artificial intelligence programming techniques to emulate the behaviour of a human expert as they solve a problem.

Location. The physical placement of a specific area.

Multimedia Representation. A representation combining many different media, such as text, graphs, drawings, sound, and video, into one database.

Observations. The phenomena physically observed on site by the evaluators.

Occupant. Any person using a given building or area.

Occupational Stress (see also ***Stress Behaviours***). A response to situations and circumstances that place special demands on an individual with negative results (Clements-Croome, Kaluarachchi, and Baizhan 1997). People that report negative attitudes toward the indoor environment also are the people expressing high job dissatisfaction or low mental well-being (stress) (Cooper and Roberston 1990) in (Clements-Croome, Kaluarachchi, and Baizhan 1997) p. 20.

Occupancy. The percentage of time office spaces are occupied.

Performance. The ability of an environment to support occupant requirements as described by evaluation criteria.

Performance Concept . A framework for building design and construction. Consists of translating human needs into user requirements (for serviceability, safety, security, comfort and functionality within the building's spaces, and for an adequate life expectancy of the building and its parts); transforming them into technical performance requirements and criteria;

implementing them in the various stages of conceptual, preliminary and detailed design, to enable cost-effective construction of buildings that provide long term satisfactory performance. The original founder of the "performance concept" is attributed to John Eberhard of the Institute of Advanced Technology at the US National Bureau of Standards (1965)

Performance, Building. The behaviour in service of a construction as a whole or of the building components (ASTM E631-89a).

Performance, Functional. "User requirements expressed in the language of the users..." (Davis and Ventre, 1990).

Performance Specifications. The results a building component must achieve in use rather than describing what it is in built form (Becker, 1990).

Performance, Technical. A translation of the user requirements into criteria that can not only be responded to directly by designers and specification writers, but which also facilitate measuring and testing for compliance. (Brand, 1994).

Physical. Construction elements in the built environment. Also, aspects of the indoor environment that are quantitatively measurable (e.g. temperature, light, sound).

Planning, Facilities. (see ***Facilities Planning***)

Planning, Scenario. A future-oriented programming process of analysis and decision making. Unlike traditional programming, it reaches into the deeper future --typically five to twenty years. Instead of converging on a single future, its essence is divergence, or the consideration of multiple futures. The product of scenario work is not a plan but a strategy. Where a plan is based on prediction, a strategy is designed to encompass unforeseeably changing conditions (Brand, 1994). "Unlike extrapolation techniques, scenarios encourage planners and managers to think more broadly about the future" p. 23 (Georgantzas & Acar, 1995). It should be noted that consensus-building procedures (like DELPHI) are particularly ill-suited for scenario-planning.

Planning, Strategic (Quality). A structured process for defining the mission and goals of an organization, and then determining the means required to reach these goals. (Nelson, 1996)

Plans, Long-range. The specific actions need to be taken now to prepare for the future. (quoted from: Lauenstein, M.C. (1986) "The failure of strategic planning" *Journal of Business Strategy.* 6(4): 75-80) p. 7) Unlike strategic plans, long-range plans change according to present conditions - what is possible at the moment.

Plans, Strategic. General guidelines for allocating resources and developing capabilities. They represent management's approach to acquiring competitive advantage, they define the business, specify the markets to pursue and identify the key resources to be developed to outperform others. Unlike long-range plans, strategies/strategic plans remain relatively consistent (Becker, 1990, p.79). Business strategies are the art and science of employing the resources (tangible fixed assets) of a firm to achieve its business objectives, (Tompkins, White, Bozer, Frazelle, Tanchoco, and Trevino 1996, 2nd) p.22.

Post-construction evaluation [PCE]. An evaluation primarily concerned with the physical performance of a building after completion of construction.

Post-occupancy evaluation [POE]. The process of systematic data collection, analysis, and comparison with explicitly stated performance criteria pertaining to occupied, built environments.

Predicted Mean Vote [PMV] and **Predicted Percentage Dissatisfied** [PPD]. A thermal comfort model used to assign a comfort vote to describe the thermal sensation of a large population of people exposed to a certain environment. PPD is the predicted percentage of dissatisfied people at each PMV. As PMV changes from plus or minus from zero, PPD increases.

Process Architecture. A workplace design process developed at MIT involving "[the engagement of a] wide array of stakeholders in rethinking the dynamic relationship between work processes and the spatial, technological, financial, and organizational environments within which these processes occur" (Horgen et al. 1999) p.13.

Program. North American term for "Brief" or "Briefing."

Program, Architectural. A definition of the building's form, primarily prepared for the architectural community (architects) (Becker, 1990).

Program, User "refers to how well the building works from end users' point of view, in this case people working in and using the building. Comfort, human dignity, and the enhancement of personal and professional identity are the principle criteria" (Becker,1990) p. 177.

Program, Facility Management. A building definition based on how well it works in use from an operational and maintenance viewpoint (cleaning, energy efficiency, etc...). For builders it may include construction issues of cost, scheduling. (Palmer, 1981)

Programming (or **Briefing**). A detailed procedure for working with the client and expected users of a building to find out exactly what they want and need and can afford. Design problem(s) are then stated in these terms. (p.178 - 179) Refers to Pena, W., 1987 (with S. Parshall and K. Kelly), *Problem Seeking*, Washington: American Institute of Architects Press and (Vischer & White, 1991).

Project Quality Plan [PQP]. An ISO 9000 tool. Includes the organization's quality goals and objectives, project description, quality requirements of the project, project team and assignment of key positions of responsibility, and a listing of applicable procedures (by reference). p.174 (Haworth 1996).

Psychological. The emotional and intellectual effect of a building or area as perceived by its occupants.

Questionnaire. The written survey used to gather "perceived" or subjective information from occupants regarding building performance.

Responsible Workplace. Workplaces derived from a strategic design and planning approach which gives building users the minimum amount of constraints at their workstations. "The Responsible Workplace puts choice back into buildings" (Leaman & Borden, 1993)

Satisfaction. Acceptable accommodation of occupant/user needs.

Scenario. A script of a play or a story, a projected sequence of events. Herman Kahn introduced the term to planning while at the RAND corporation in the 1950s. It was first used by RAND in military strategy studies for the US Government. (Georgantzas & Acar, 1995).

Stress Behaviour. Evidence of a person's physical or psychological discomfort with their work environment. It can manifest itself in adaptation, having low energy, avoidance, poor communication, or pain (Smith & Kearny, 1994).

Task Area. The partial area in the workplace in which the visual task is carried out. For places where the size and location of the task area is unknown, the area where the task may occur shall be taken as the task area. (CEN:prEN 12464 1998, prEN 12464)

Time Utilization Study [TUS]. An observation measurement technique. Used to determine how effectively time and space are being used in an office by noting hourly the activity within a workspace during a workday for given period (usually two weeks) (Duffy, 1997) p. 227.

Well-being. Physical and mental health of an individual (Clements-Croome, Kaluarachchi, & Baizhan, 1997). *Subjective well-being* refers to awareness and satisfaction with life among populations.

Work Area. A small area, often including space for meetings and common equipment, where a discrete work group of any size works. Self-directed work teams fit in here.

Work Environment. A generic term referring to a place of any size where work occurs.

Workplace (or **Floor Area**). An area within an office building where many people or groups work. (see also **Responsible Workplace**)

Workspace (or **Workstation**). An individual area where one person works.

Samenvatting

Het doel van dit promotieonderzoek is het realiseren van een basis om het vergaren en toepassen van kennis op het gebied van prestaties van kantoorgebouwen in de ontwerpfase te ondersteunen. Meer specifiek zijn de doelstellingen (1) het ontwikkelen van een prestatiegebaseerde aanpak om technische kennis verkregen met gebouwevaluatie na in gebruik name, (Post-Occupancy Evaluation [POE]), van bestaande en innovatieve werkplekomgevingen te hergebruiken en daarmee creativiteit te stimuleren en het nemen van vroege beslissingen te kunnen voeden, en (2) het beschouwen van de potentie om door middel van een "intelligente" informatie technologie ondersteuning voor deze aanpak te leveren.

De onderliggende motivatie voor dit onderzoek is de behoefte om de kwaliteit van het binnenmilieu van werkplekken te verbeteren. De impact van binnenmilieufactoren op de gezondheid en het welbevinden van kantoormedewerkers wordt onderkend. In de afgelopen jaren zijn organisaties zich tevens bewust geworden van de strategische impact die het ontwerp van werkplek omgevingen heeft door directe en indirecte invloed op het bedrijfsresultaat. Sommige onderzoekers suggereren dat een deel van het probleem terug te herleiden is naar een gebrek aan integratie van technische prestaties door architecten bij het nemen van beslissingen in de vroege ontwerpfase. Deze studie legt als hypothese neer dat het mogelijk zou moeten zijn bij te dragen aan de verbetering van de kwaliteit van het nemen van beslissingen in de vroege ontwerpfase door ondersteuning te ontwikkelen voor de overdracht van technische prestatiekennis, verkregen door POE uit eerdere ontwerpcycli, naar de vroege ontwerpfases van nieuwe ontwerpcycli.

Deze studie begint met het uitwijden over de aard van het proces van het nemen van ontwerpbeslissingen, die het voorheeft te ondersteunen — Strategische Planning en Evaluatie van Gebouwprestaties, (Strategic Building Performance Planning and Evaluation [SBPPE]). Daarna ontwikkelt het een algemene specificatie en een driedimensionaal matrixmodel van het domein van de evaluatie van de prestaties van kantoorgebouwen in termen van zijn gebruikerseisen, elementen van gebouwsystemen, en gebouwniveaus. Het meten van de gebouwprestatie – de technische doelstelling – is geformuleerd op basis van de intersecties afgeleid van het model. De studie laat zien hoe verschillende doelstellingen helpen om het niveau van overeenstemming te bepalen tussen eisen en elementen. Daarmee faciliteert het het vergaren en hergebruiken van kennis in termen van prestatierelaties.

Om de tweede doelstelling van deze studie te kunnen realiseren is een Case-Based Reasoning [CBR] aanpak geselecteerd. De toepasbaarheid ervan op het gebied van ontwerpen is geanalyseerd door middel van een literatuurstudie. De studie legt uit hoe CBR een kunstmatige intelligentie techniek is, die in het verleden op het gebied van architectuur is toegepast, om ontwerpers in staat te stellen hun efficiëntie te vergroten en om kosten te besparen door automatisering van de herinnering aan en het hergebruik van oude ontwerpen voor nieuwe ontwerpsituaties. Op basis van de analyse van bestaande applicaties is de rol van het CBR gereedschap voor de doelstellingen van deze studie geïdentificeerd als het stimuleren van leren en het voeden van het nemen van beslissingen met betrekking tot technische onderwerpen in de vroege ontwerpfase. Dit gebeurt door actuele POE prestatieresultaten van cases van bestaande werkplekken te relateren aan prestatie-eisen voor een nieuwe werkplekomgeving.

De conceptuele haalbaarheid van de aanpak is op verschillende manieren getest door middel van het ontwerp en de implementatie van een theoretisch Case-Based Reasoning gereedschap, Workplace Environment Design Assistant [WEDA] genaamd. De eerste test is een verdere uitdieping van een deel van het domeinmodel, specifiek gerelateerd aan comfort en welbevinden op de werkplek. De resulterende kennismodellen voor combinaties van eisen en elementen zijn gevalideerd met drie domeinexperts. Door als basis gebruik te maken van technische doelstellingen uit het model is een POE gereedschapskist ontwikkeld, waarmee data van bestaande werkplekken is verzameld en vertaald in cases. Een proces (taak) model van de vroege fases van prestatiegericht ontwerpen is geïntroduceerd, om te identificeren of en wanneer technische prestatie kennis bruikbaar zou kunnen zijn bij het ondersteunen van vroege ontwerpbeslissingen betreffende werkplek omgevingen. Gebaseerd op het procesmodel is een (regel) strategie gerealiseerd voor de instrumentele ondersteuning om eerst eisen uit het programma van eisen te vertalen in technische doelstellingen en daarna cases op te roepen uit de bibliotheek van cases. Deze strategie is geïmplementeerd in een WEDA prototype. Het prototype is getest tijdens een focusgroep workshop.

Deze ervaring laat zien dat de theoretische aanpak zowel haalbaar als bruikbaar blijkt te zijn voor het ondersteunen van vroege ontwerpbeslissingen met betrekking tot de selectie van concepten van gebouwsystemen in relatie tot ontwerpeisen voor een nieuwe werkplek. Voordat echte beslissingen ondersteund kunnen worden zou echter de inhoud van het huidige kennismodel verder uitgediept moeten worden. Tevens zou de eigenschap van de technische doelstellingen om de geschiktheid van een binnenmilieu te voorspellen verder gevalideerd moeten worden. Het prototype WEDA toont de conceptuele haalbaarheid van de aanpak aan, en representeert een eerste stap in de richting van het formuleren van aanpakken om het vergaren en het verspreiden van technische prestaties in de vroege ontwerpfases te ondersteunen.

Summary

The aim of this doctoral research is to establish a basis for supporting the acquisition and application of knowledge related to office building performance in design. More specifically, its objectives are to (1) develop a performance-based approach for re-using the technical knowledge gained from the Post-Occupancy Evaluation [POE] of existing and innovative workplace environments to stimulate creativity and inform early decision-making, and (2) consider the potential of providing support for this approach by means of an "intelligent" information technology.

The underlying motivation for this research is the need to improve the quality of indoor environments of workplaces. The impact of environmental factors on the occupational health and well-being of office workers is acknowledged. In recent years, organizations have also become aware of the strategic impact that the physical design of workplace environments has by directly and indirectly influencing business outcomes. Some researchers suggest that part of the problem can be traced back to a lack of integration of technical performance by architects in their early design decision-making. This study hypothesizes that it should be possible to help improve the quality of early design decision-making by developing support for the transfer of technical performance knowledge gained through POE from previous design cycles into the early stages of new design cycles.

This study begins by elaborating on the nature of the design decision-making process this research intends to support — Strategic Building Performance Planning and Evaluation [SBPPE]. It then develops a general specification and a three dimensional matrix model of the office building performance evaluation domain in terms of its human requirements, building system elements, and architectural scales. The measurement of building performance – the technical target – is formulated based on the intersections deduced from the model. The study shows how various targets help to measure the level of suitability between requirements and elements, and hence facilitate the acquisition and re-use of knowledge in terms of performance relationships.

To address the second objective of this study, a Case-Based Reasoning [CBR] approach is selected and its application to design is analyzed through domain literature. The study explains how CBR is an artificial intelligence technique that has been applied to the field of architecture in the past to enable designers to increase their efficiency and reduce cost by automating the recall and re-use of past designs for new design situations. Based on analysis of existing applications, the roles of the CBR tool are identified as to stimulate learning and inform early decision-making regarding technical issues. The tool will do this by relating actual POE performance outcomes of existing workplace cases to new workplace environment performance requirements.

The conceptual feasibility of the approach is tested in several ways through the design and implementation of a theoretical Case-Based Reasoning tool called Workplace Environment Design Assistant [WEDA]. The first test is a further elaboration of a portion of the domain model specifically relating to workplace comfort and well-being. The resulting requirement-element knowledge models are validated with three domain experts. Using technical targets from the model as a basis, a POE toolkit is developed and data is collected from actual workplaces and translated into cases. A process (task) model of the early stages of performance-based design is introduced, to identify if and when technical performance knowledge might be useful in supporting early design decisions concerning workplace environments. Based on the process model, a (control) strategy for instrumental support to first translate briefing requirements into technical targets and then recall cases from a case-library is established and then implemented in a WEDA prototype. The prototype is then tested with a focus-group workshop.

This experience shows the theoretical approach appears to be both feasible and useful for supporting early design decisions concerning the selection of building environmental system concepts in relation to new workplace design requirements. Before real decisions could be supported, however, the content of the current knowledge model would need to be elaborated and the ability of the technical targets to predict the suitability of indoor environments would need to be validated further. The prototype of WEDA demonstrates the conceptual feasibility of the approach, and represents an initial step along the formulation of approaches to support the acquisition and dissemination of technical performance in early design.

Curriculum Vitae

Shauna Hill was born and raised in Winnipeg, Manitoba, Canada. The daughter of an artist and a neurosurgeon, she is the youngest of five children. She has a Bachelor of Environmental Studies [B.E.S] and a Master's of Architecture [M.Arch.] both from the University of Manitoba. After working in practice and serving as Director of the Canadian Institute for Barrier-free Design (1992-95), she moved to the Netherlands to undertake her Doctoral research in 1996. Shauna married Shaun Mallory in 1997. Their daughter Annemiek was born in Eindhoven two years later. The Mallorys returned to Canada in 2000. In 2001, Shauna became an Assistant Professor in the Faculty of Architecture at the University of Manitoba. She continues to research and publish in the areas of workplace performance evaluation and design decision support tools for designers.

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associated with the dissertation

Supporting Strategic Design of Workplace Environments with Case-Based Reasoning

Shauna M. Mallory-Hill

I

As a profession, architecture seems to draw an unfortunate distinction between research and professional practice. The lack of integration of Post Occupancy Evaluation with architectural design practice means that architects are unable to access and incorporate this experience and knowledge into their decision-making process. *(This thesis, Chapter II.)*

II

Organizations are becoming aware that workplace environments are indirectly or directly affecting worker productivity. Increasingly, workplace design will become recognized as part of gaining or maintaining a competitive business advantage. *(This thesis, Chapter II.)*

III

The ideal role for Case-Based Reasoning is as a design *aiding* tool rather than a design *generating* tool. *(This thesis, Chapter III.)*

IV

At a fundamental level, performance-based language and logic allows the design professional to transcend the prescriptive and technical description of what a workplace design *is*, and begin to think of it more strategically, by what it *does*. *(This thesis, Chapters II and VIII.)*

V

"An intelligent building is one that doesn't make the occupants look stupid."
– Anon (source: www.usablebuildings.co.uk)

VI

Architectural research can be differed from pure scientific research in that architecture cannot be separated from context. For example, the replica Eiffel Tower in Las Vegas, Nevada, though meticulously rendered at ½ scale, is physically and temporally different than the original in Paris, France.

VII

"It takes an architect to think up the problems which can only be solved by an engineer." *– Bret Askew, Architect & Structural Engineer.*

VIII

"I have not failed, I have found 10,000 ways that don't work."
– Thomas Edison, US Inventor, 1847-1931.

IX

Giving birth to a baby and giving birth to a doctoral dissertation have much in common; both are stressful, painful and require a sense of humour to survive.

X

"The cure for boredom is curiosity. There is no cure for curiosity."
– Dorothy R. Parker, (1893-1967),
Author & founder/member of the "Algonquin Round Table."

XI

"Whatever you can do or dream, begin it.
Boldness has genius, power and magic in it."
– John Anster, 1835 translation of Goethe's "Faust."