FULL TITLE
Modeling support systems for multi-modal design of physical environments

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ABSTRACT
This paper studies the development of support systems for the improvement of environmental quality in office environments. First three types of representation required for different aspects of designing are discussed: (1) integrated modeling to represent physical behavior, (2) multi-dimensional formulation of required behavior and (3) multi-modal representation to support human design appraisal and modeling. In the following step the adaptive change process is compared to the design process for future artifacts in order to differentiate design activities which advance the design or change the design problem from activities which change the activities of designing and the systems that support them. For this differentiation six design processes are formulated formally adopting Gero’s original FBS framework. One of these processes is the actual design process and the five others develop support systems for the activities of designing: formulation, analysis and evaluation and the interfaces for structure and function manipulation. As a result of the discussion the evaluation statement E and the design intervention I are added to the FBS framework to enable formal formulation of the reformulation processes. Ten reformulation processes are identified. One progresses the structure (synthesis) another changes the design problem (reformulation), while the remaining eight adapt design support functions to the needs of the on-going design process. Through discussion of these processes representation requirements – integrated, multi-dimensional and multi-modal – are mapped to the activities of designing. At the end of the paper the developed framework is applied in three case studies discussing the development and the application of design support systems, using occupant surveys, environmental measurement and integrated computational simulation. The application of the framework in these case studies demonstrates the various modes of representation and the significance of their interplay for dynamic design development and the development of systems to support such design development effectively.

KEYWORDS
design model
design support system
integrated representation
multi-dimensional representation
multi-modal representation
1. INTRODUCTION

Architectural design is an activity with significant implication on the future behavior of human environments. Architects modulate this behavior by creating physical structures (social, organizational and other structures are also created, but not discussed in this paper), which interact with environmental influences, active service systems and with the activities of the occupants within them. Such interaction results in new behavior of the environment, which again affects the performance of all its components. Dynamic behavior emerges through complex interaction and changing the structure results in changes in multiple aspects of dynamic environmental performance. Therefore the behavior of designed objects is a complex, highly integrated and dynamic phenomenon.

On the other hand the performance of the environment is perceived by occupants in multiple modes. Looking only at comfort perception in the built environment (to confine the discussion to the scope of the presented work) research indicates that the quality of an environment cannot be assessed using one integrated or representative measure. For example Vischer (1996) uses the term ‘comfort dimensions’ in her comfort evaluation framework, in order to acknowledge that occupant perception votes on specific aspects of comfort do not correlate with each other and Humphreys (2005) shows that votes on specific comfort aspects do not correlate with overall comfort perception votes collected. Therefore environmental evaluation requires multi-dimensional formulation of required qualities.

The third aspect in this discussion relates to human reasoning capabilities in the design process. According to Akin (1978) designers can deal only with one design goal at a time and Darlington et al. (1998) name decomposition as the principle to approach complex design problems. Decomposition can utilize multiple structuring, reduction and other analysis techniques and it results in representations in which aspects of the design problem are omitted in order to emphasize others. Consequently complete design reasoning requires multiple complementing modes of representation. These modes either address different domains or they support different types of reasoning about the same issue. Decomposition techniques are applied in order to describe the intended functions, to define the expected behavior and to manipulate the designed structure. As all these representations deal with the same design object, they are implicitly connected. Their interrelation introduces complexity in the design task. Therefore multiple modes of design representation and explicit knowledge about their connection or implicit functions to translate between them are required in order to support design development.
From this short discussion we learn that three types of representation are required in order to describe relevant components of the design development process:

1. integrated modeling, in order to analyze the behavior of the designed artifact,
2. multi-dimensional formulation, in order to formulate its necessary behavior, and
3. multi-modal representation, in order to support modeling and evaluation by human designers.

Another characteristic of architectural design which affects all three types of representation is the temporal distance between the act of designing and the actual performance of the design object in the natural and social world. According to Gero (1990) design is purposeful and a goal-oriented activity, which turns expected purposes or functions (not the actual function) of the resulting artifact into design description (not into the artifact itself). This distance requires the application of predictive representation techniques and adds further complexity to the task of implementing such representations in computational systems.

As a design task in the architectural domain is usually extensive and complex, extensive and multi-layered representations of the design object and its context have to be constructed, maintained and developed while designing. The interpretation of these representations is situated. How the information contained is transformed and utilized in the process of designing depends on the perception and the previous experience of the assessor, as well as on the dynamic context of the design process (2004). It obviously also depends on the formulation and the complexity of the representation itself.

Not all goal-oriented, constraint, decision-making, exploration, and learning activities, which have the purpose to change the environment and its future performance are temporally detached. Section 2 will discuss scenarios of change processes in which artifacts are actually created and evaluated concurrently in order to understand which aspect of complexity is introduced by the representation and which aspect of complexity is originated in the actual design task. In the following section the three types of representation are mapped to Gero’s original FBS framework in order to develop requirements for systems to support specific activities and aspects of designing.

2. CHANGE AND DESIGN PROCESS SCENARIOS

2.1. Overview

Three change and design process scenarios are discussed in this section. Gero’s original FBS framework (1990) has been adopted and extended in order to compare characteristics of the human-driven adaptive change process and the human-driven conventional design process and to lay the foundation for the formulation of the augmented design process in section 3.
The purpose of section 2 is to identify components in the human-driven change process which are implicitly defined by the context of the designed artifact and the domain context in distinction to components which require human decision making at design time. The discussion differentiates between design of design aids (such as representations, behavior models and interfaces) and the design of the artifact in order to identify components, which are best represented with an integrated, multi-dimensional or multi-modal representation.

2.2. Adaptive change

Adaptive change is an explorative development in incremental circles of change and evaluation actions performed on the actual artifact in its actual world by its actual user. The change events in this scenario are simple and are possibly performed subconsciously. Change does not necessarily result in optimized systems, but in satisficing outcomes (Simon, 1996; Brand, 1994).

The F-Be transformation (‘formulation’ activity in the original FBS framework) is not performed consciously as the expected function and the expected functioning (behavior) are closely connected in the actor’s mind. Neither the set of required functions nor a description of the expected behavior is formulated explicitly. Explicit reasoning and external representation is not required.

Also the SC-Bs transformation (‘analysis’ activity in the original FBS framework, extended by C for ‘context’) is not performed consciously as the actual behavior of the structure ‘happens’ in the actual world. Explicit reasoning and external representation neither of the structure nor of its behavior is required as the behavior is perceived by the actor and is then instantly present in the actors mind.

Evaluation (Be-Bs comparison) is performed based on the expected behavior Be and the perception of the actual performance Bs. New incremental change actions are initiated when the actor perceives dissatisfaction with the new situation or if he sees that opportunities for improvement have arisen.

Such incremental change can not be performed freely; it is constrained through the structure. For example Brand (1994) drafts the SSSSSS framework and uses the categories site, structure, skin, services, space plan and stuff
(furniture, etc.) to differentiate the parts of an existing building to which change can be made easily (such as the
stuff and the space plan) from parts which are permanent (such as the site and the structure).

Adaptive change processes evolve in owner occupied buildings (Brand, 1994) where expected functions do not
have to be negotiated, where change is not constraint by lease contracts and where evaluation is seamless and an
on-going process. A similar situation exists in software development, where the performance of the developed
code (structure) can be instantly evaluated in its designated environment. Functions and the expected behavior
are closely connected, if not identical. Kruchten (2005) describes this process as follows: “Iterative development
lets us work on both sides of the evaluation process (Be to Bs), and not only simply fix S to achieve the right Bs.
We call this process design emergence and refactoring. Iterative development and agile methods exploit the
reformulation processes, in particular behavioral and structural reformulation. Involving customers throughout
the development process by showing them intermediate versions of the structure results in changes in the set of
functions or expected behaviors. The evolution of software developments life cycles, techniques, and tools for
supporting the various processes led to this shift of emphasis from straight synthesis to loops and
reformulations.” Fischer and Scharff (2000) argue in the same direction to close the gap between software
designer and software user by providing open software systems, which allow the actual user to modify the
implementation freely in order to achieve software capabilities which meet the actual needs. Adaptive change is
characterized by seamless formulation F-Be and analysis SC-Bs and intuitive evaluation Be-Bs.

2.3 Design

Characteristic for architectural design is the temporal distance between the act of designing and the performance
of the designed artifact. Behavior Bs can not be observed like in the adaptive change process as the actual
artifact S and its context C is not available for investigation at design time. Also the required functions F and the
expected behavior Be can only be predicted. The formulation and content of the Be and Bs representations
derived through formulation F-Be and analysis SC-Bs determine the significance of the evaluation for the
prediction of the actual performance of the future artifact. Usually F-Be and SC-Bs are performed under
application of multiple parallel formal and informal representations. These representations are in-coherent,
which adds substantial degrees of complexity to a process of designing.

Conventional design is characterized by separation of expected functions F and expected behavior Be, separation
of structure S and behavior derived from structure Bs and separation of the expected behavior Be and behavior
derived from structure Bs. Therefore formulation F-Be, analysis SC-Bs and evaluation Be-Bs involve application
of in-coherent representations and models and demanding cognitive actions within and in between various
worlds of representation (Gero, 2004). All three, formulation, analysis and evaluation, are affected by the situatedness of the designer’s cognition and reasoning.

2.4 Augmented design

Computational augmented design aims to utilize the strengths of the adaptive change process for the design of future artifacts through application of computational models (and other systematic models) developed to bridge the separation between the components of the design process. Computational augmented design aims to confine the effects of situated cognition and reasoning to components of the design process which either develop the design task F or develop the designed artifact S. Components which represent natural and physical behavior (SC-Bs), which are defined through scientific models (F-Be) or which perform objective processing of available data (Be-Bs) are, as far as possible, supported through design aids and support systems in the augmented design process.

Five components of the augmented design process are discussed in regard of representation requirements for the example of designing comfortable physical environments. The five components are: formulation (F-Be), analysis (SC-Bs), evaluation (Be-Bs) and the interfaces to manipulate the set of functions and the designed structure S.

Section 3 develops a framework for the development of support systems in the context of the design process based on the FBS framework. Section 4 applies the framework in three case studies of change design applications which involve various different types of representations.

3. DESIGN OF ARTIFACTS AND DESIGN OF DESIGN AIDS

3.1. Framework

In order to understand the design of the design aids for the augmented design process a two layered framework of six FBS design prototypes is employed as shown in Fig. 2. The actual design process is depicted in the middle aiming to transform the set of functions F into a representation of the structure S. The remaining five design prototypes describe the design of aids for the activities of designing.
Fig. 2. Two layered framework of FBS design prototypes; layer 1: design development S, layer 2: design aid development $M^f$, $M^e$, $M^a$, $I^s$ and $I^f$

3.2. Modelling

3.2.1. Explanation

This paragraph explains the notation used for modeling the design processes shown in Fig. 2. Items in curly brackets {} refer to sets of variables, while items without brackets refer to actual values relevant for the specific design task discussed. The central design process in Fig. 2 changes the values, while the five design processes of the support systems change the sets of variables, their representations and their interfaces. The symbol “$A \rightarrow B$” reads “A results in B” and the symbol “$A \diamond B$” indicates that a function dataset A is transformed into a structure dataset B through design activity. An apostrophe ‘ indicates a reformulated version of a previously used dataset or data structure as result of design and refinement activity. The symbol “$A \in B$” means that “A is an element of B”. The items of the discussion are best understood in reference to Fig. 2.

3.2.2. Function interface

The function interface $I^f$ is derived from the analysis of requirements R under application of knowledge how occupants perceive environments Kp and knowledge Kc about how the designer’s cognitive activities can be supported.

$R, Kp, Kc \rightarrow F^f \diamond I^f \rightarrow I^f$

{$F$} $\in I^f$

The function dataset F is entered via the interface $I^f$ through active design intervention I by the designer.

$F = I^f(I)$
3.2.3. Formulation model $M^f$

The set of function variables \{F\} and knowledge how occupants perceive environments $K_p$ are transformed into a set of function variables $F^f$ for the development of formulation model $M^f$. Design activity $F^f \circ M^f$ results in the formulation model $M^f$. The data structures \{F\} and \{Be\} are elements contained in the model.

\[
\{F\}, K_p \rightarrow F^f \circ M^f \rightarrow M^f
\]

\[
\{F\}, \{Be\} \in M^f
\]

Be results from application of $M^f$ as a function of F.

$Be = M^f(F)$

$M^f(F)$ might result in a reformulation of $F$ when instances of the function dataset interfere with each other. For example the function dataset has to be emended when good acoustic privacy and good communication properties are required at the same time as these two functions contradict each other.

$F' = M^f(F)$

3.2.4. Analysis model $M^a$

The set of expected behavior variables \{Be\} and knowledge on the physical behavior of the environment $K_s$ are transformed into a function dataset $F^a$. Design activity $F^a \circ M^a$ results in the analysis model $M^a$. The data structures \{Bs\}, \{S\} and \{C\} are elements contained in this model.

\[
\{Be\}, K_s \rightarrow F^a \circ M^a \rightarrow M^a
\]

\[
\{Bs\}, \{S\}, \{C\} \in M^a
\]

Bs results from application of $M^a$ as a function of S and C.

$Bs = M^a(S, C)$

3.2.5. Structure interface

The structure interface $I^S$ is derived from \{S\} under application of knowledge on how the environment behaves $K_s$ and knowledge $K_c$ how to support human design reasoning. The set of structure variables \{S\} is an element of the structure interface $I^S$.

\[
\{S\}, K_s, K_c \rightarrow F^S \circ I^S \rightarrow I^S
\]

\[
\{S\} \in I^S
\]

The values in the structure dataset $S$ are entered via the interface $I^S$ through design intervention $I$.

$S = I^S(I)$
3.2.6. Evaluation model $M^e$

The behavior data structures $\{B_e\}$ and $\{B_s\}$ obtained through $F \diamond M^f$ and $SC \diamond M^f$ are transformed under application of knowledge $K_p$ on how environments are perceived and knowledge on how to support human design reasoning $K_c$ into the evaluation model $M^e$. In this process $\{B_e\}$ and $\{B_s\}$ are reformulated in order to match both sides of the evaluation model $M^e$ and in order to enable modes of representation suitable for automatic evaluation and supportive for human reasoning and decision making.

$\{B_e\}, \{B_s\}, K_p, K_c \rightarrow F^e \diamond M^e \rightarrow M^e$

$\{B_e,'\}, \{B_s,'\} \in M^e$

The result of the evaluation model $M^e$ is an evaluation statement $E$.

$E = M^e(\{B_e, B_s\})$

3.2.7. Interpretation $r_0$

The evaluation statement $E$ is interpreted through $r_0$ (see Fig. 3) under consideration of the knowledge $K$ available to the designer into an intended design intervention $I$. $r_0$ involves creative design and subjective decision making, it utilizes the designer’s experience and other types of knowledge.

$I = r_0(E, K)$

$K_p, K_c, K_s \in K$

Process $r_0$ can be understood as the cognitive process which is to be supported by the developed support systems. It transforms an evaluation statement $E$ into a plan for a design intervention $I$ in the current context of the ongoing design process. Therefore $r_0$ can be formulated:

$r_0: E \diamond I \rightarrow I$

3.3. Design development and model refinement

After the processes for the computational design support system development are modeled formally their application in the design process is reviewed. Two types of activities are differentiated. The left hand side of Fig. 3 shows the design development activities which change the designed structure $S$ and the design task $F$. These reformulations advance the actual design. The right hand side depicts the activities which change the support processes and systems.
3.3.1. Design development activities

Reformulation activity $r_1$ is the synthesis activity. The intended design intervention $I$ triggers the reformulation of $S$. It is actioned through the structure interface $I^S$ as a function of the intended design intervention $I$ and the current structure representation $S$.

$$r_1: S' = I^S(I, S)$$

Reformulation activity $r_2$ changes the expected functions or the purpose of the designed artifact. The intended design intervention $I$ triggers the reformulation of $F$. It is actioned through the function interface $I^F$ as a function of intended design intervention $I$ and the current function representation $F$.

$$r_2: F' = I^F(I, F)$$

Activity $r_2$ is actioned, when either the means of $r_1$ to achieve the specified functions through structure reformulation are exhausted (relaxation) or if it is recognized that more definition of the expected functions is required (specification) in order to optimize the design outcome.

3.3.2. Process refinement activities

Model refinement activity $r_3$ is closely related to activity $r_1$. It is triggered when the structure of the designed artifact is to be changed, but when the structure interface $I^S$ does not allow to change or to present the required values of $S$ effectively. Therefore two types of the process are differentiated: $r_{31}$ adds new modes of representation to the interface $I^S$ and $r_{32}$ extends the existing formulation of $\{S\}$ and the interface to manipulate $S$.

$r_{31}$ employs knowledge $K_c$ on how designers can be supported when manipulating the representation of the designed artifact. $r_{32}$ employs knowledge $K_s$ on how the environment behaves and results in reformulation of $\{S\}$.
Model refinement activity \( r_f \) is closely related to process \( r_2 \). It is triggered when the expected function of the designed artifact is to be changed, but when the function interface \( I^F \) does not provide the means to change or to represent the required values of \( F \) effectively. Therefore two types of the process are differentiated: \( r_{f1} \) adds new modes of representation to the interface \( I^F \) and \( r_{f2} \) extends the existing formulation of \( \{F\} \) and the interface to manipulate \( F \).

\( r_{f1} \) employs knowledge \( K_c \) on how designers can be supported when manipulating the representation of the functions and requirements. \( r_{f2} \) employs knowledge \( K_p \) on how the environment’s behavior is perceived by occupants. \( r_{f2} \) results in reformulation of \( \{F\} \).

\[
r_{f1}(I, \{S\}, K_c) \rightarrow F^S \odot I^S \rightarrow I^S^r
\]
\[
r_{f2}(I, \{S\}, K_s) \rightarrow F^S \odot I^S \rightarrow I^S^r
\]
\[
\{S\}^r \in I^S^r
\]

Model refinement process \( r_e \) is triggered through \( I \) when the evaluation statement \( E \) does not provide enough information to trigger either of the design development processes \( r_1 \) and \( r_2 \) due to insufficient information provided by \( M_e \) in \( E \) or due to ineffective representation of \( E \). Therefore two reformulation processes are differentiated: \( r_{e1} \) aims to improve the representation of \( E \), it employs knowledge \( K_c \). \( r_{e2} \) has the objective to change the information generated through \( M_e \), it employs knowledge \( K_s \) and \( K_p \). \( r_{e2} \) might lead to reformulation of \( \{Be\} \) and \( \{Bs\} \) as these are elements of \( M^e \).

\[
r_{e1}(I, \{Be\}, \{Bs\}, K_c) \rightarrow F^E \odot M^e \rightarrow M'^e
\]
\[
r_{e2}(I, \{Be\}, \{Bs\}, K_s, K_p) \rightarrow F^E \odot M^e \rightarrow M'^e
\]
\[
\{Be\}' \in M'^e
\]
\[
\{Bs\}' \in M'^e
\]

Model refinement process \( r_f \) is triggered through \( I \) when the evaluation statement \( E \) does not provide enough information to trigger either of the design development processes \( r_1 \) and \( r_2 \) due to insufficient information provided in \( Be \). \( I^F \) is reformulated under consideration of \( I \) and \( K_p \). \( M^f \) is developed as depicted through design activity in Fig. 2. \( r_f \) leads to reformulation of \( \{F\} \) and \( \{Be\} \) as these are elements of \( M^f \).

\[
r_f(I, \{F\}, \{Be\}, K_p) \rightarrow F^F \odot M^f \rightarrow M'^f
\]
\[
\{F\}' \in M'^f
\]
\[
\{Be\}' \in M'^f
\]
Model refinement process $r_a$ is triggered through $I$ when the evaluation statement $E$ does not provide enough information to trigger either of the design development processes $r_1$ and $r_2$ due to insufficient information provided in $B_s$. $F^a$ is reformulated under consideration of $I$, $K_s$. $M'^a$ is developed through design activity as depicted in Fig. 2. $r_a$ might lead to reformulation of $\{S\}$, $\{C\}$ and $\{B_s\}$ as these are elements of $M^a$.

$$r_a(I, \{S\}, \{C\}, \{B_s\}, K_s) \rightarrow F^a \diamond M^a \rightarrow M'^a$$

$\{B_s\}'$, $\{S\}'$, $\{C\}' \in M'^a$

### 3.4. Summary

The previous discussion differentiates between activities which advance the development of the actual design task and activities which improve the process of designing and the systems to support them. The first group of processes can be summarized as follows:

$$S' = I^f(r_o(M^f(F), M^f(S, C)), K), S)$$

$$F' = I^f(r_o(M^f(F), M^f(S, C)), K), F)$$

$$K_p, K_c, K_s \in K$$

The structure $S$ and the design task $F$ are developed iteratively. The context $C$ is not changed (per definition of $S$ and $C$, although content might shift from $C$ to $S$). The design development is based on knowledge $K$ and the knowledge implemented in the models $M^e$, $M^f$, $M^g$ and in the interfaces $I^e$ and $I^f$.

Interesting is the interpretation process $r_0$ in the center of the developed model. It represents how designers interpret the conceived information internally and action on what they perceive and understand. $r_0$ involve complex decision making and creative design activity.

In order to summarize the support system’s development the activities initially described in section 3.2 are understood as special cases of reformulation activities described in section 3.3. The initial requirement statement $R$ is then an evaluation statement $E$ assessing the unchanged situation. The initial $I^g$ is the formulation chosen to articulate the perceived demand. The following statements are derived for all components:

$$r_{S1}(r_o(M^f(F), M^f(S, C)), K), \{S\}, K_c) \rightarrow F^g \diamond I^g \rightarrow I'^g$$

$$r_{S2}(r_o(M^f(F), M^f(S, C)), K), \{S\}, K_s) \rightarrow F^g \diamond I^g \rightarrow I'^g$$

$$r_{F1}(r_o(M^f(F), M^f(S, C)), K), \{F\}, K_c) \rightarrow F^g \diamond I^g \rightarrow I'^g$$

$$r_{F2}(r_o(M^f(F), M^f(S, C)), K), \{F\}, K_p) \rightarrow F^g \diamond I^g \rightarrow I'^g$$

$$r_{B1}(r_o(M^f(F), M^f(S, C)), K), \{B_e\}, \{B_s\}, K_c) \rightarrow F^g \diamond M^e \rightarrow M'^e$$

$$r_{B2}(r_o(M^f(F), M^f(S, C)), K), \{B_e\}, \{B_s\}, K_s, K_p) \rightarrow F^g \diamond M^e \rightarrow M'^e$$

$$r_{F}(r_o(M^f(F), M^f(S, C)), K), \{F\}, \{B_e\}, K_p) \rightarrow F^g \diamond M^f \rightarrow M'^f$$
ra(r0(Me(Mf(F), Ma(S, C)), K), {S}, {F}, {Bs}, Ks) → Fa ◊ Ma → Ma'

All eight reformulation processes are triggered through I by E. E is the result of Me. Me processes the results of Mf and Ma. The input variables of these processes are the current F, S and C. All reformulation processes require the data structures of the components included in the model or interface they change and various types of knowledge Kc, Ks and Kp.

The matrix in Fig. 4 orders the reformulation processes and representation types required to the components of the support system and its interfaces. It must be mentioned that multi-dimensional representation is used to model multi-modal as well as integrated representations in common support system developments.

Fig. 4. Matrix of representation types for development of support systems and interfaces derived via necessary knowledge types

The matrix shows that the structure interface bridges between integrated and multi-modal representations. The function interface bridges between multi-dimensional and multi-modal representations and the evaluation model translates multi-dimensional and integrated representations into a multi-modal representation. While the formulation model and the analysis model mainly deal with multi-dimensional and integrated representation types respectively.

Another way to approach the developed framework is to look at links between the elements of the models. It is apparent that the capabilities of one component constraint the significance of the other components and that the reformulation of one component possibly results in new opportunities to achieve more significant information through the others.

4. CASE STUDIES

4.1. Overview

After the design development processes and process refinement processes are formulated formally the derived framework is applied in discussion of three design support systems. Case 1 is the development of physical environments under application of occupant surveys; case 2 is the improvement processes which involve
environmental in-situ measurement and case 3 describes the development of a design support system based on computational simulation. Cases 1 and 2 have characteristics of adaptive change and augmented design; while case 3 describes the development of a computationally augmented design system (see Fig. 5). The initial formulation of the processes of all three cases and some discussion on their development is given in the following sections.

**Fig. 5.** Design development for three environmental assessment and design development application cases (legend see Fig.3)

### 4.2 Occupants survey

#### 4.2.1 Description

Case 1 describes an improvement process under application of occupant surveys. In this case the design object is available for investigation and development at design time. Examples for this application are described in more depth in (Purdey, 2007; Vischer, 1996). The elements of the process are allocated as follows:

**Formulation**

- **F** problem statement
- **F’** questionnaire topics defining the dimensions of office environmental quality
- **M’** questions on specific aspects of the dimensions of environmental quality
- **Be** benchmarks and target values determined by statistical analysis of Bs datasets derived in similar previous studies in the structure of the questionnaire given through M’.

**Analysis**

- **S** change opportunities and constraints provided by structure, change capabilities and organizational and financial means
- **C** office environment defined through physical, social and organizational properties
- **E** climate, physical, social and organizational environment
perceptual, cognitive and affective appraisal of the situation formed in the assessor’s mind in the
structure of the questionnaire given through $M^f$. Modeling of $M^a$ is not required as the structure’s
behavior is perceived directly by the occupant in the physical world.

Bs perceptual, cognitive and affective appraisal stated in the questionnaire given through $M^f$

Evaluation

$M^e$ statistical analysis of votes from a group of subjects, combined representation of $B_e$ and $B_s$ in various
modes (tables, diagrams, indices)

$E$ ranking, Boolean statement, relative performance statement, prioritization of performance aspects,
design advice

$I$ plan how to progress the design

4.2.2 Discussion: occupant survey

Fig. 6 shows the development of the components of a building diagnostic study under application of occupant
surveys. General function statements $F$ in form of environmental quality dimensions are represented through a
catalogue of questions $M^f$ on aspects of these dimensions. Each question requests a rating of the perceived
environmental performance or on self-assessed performance of the participant on a rating scale.

The catalogue of questions is derived from previous studies in which the significant questions for a specific
environmental quality dimension are determined. Statistical analysis of votes collected in previous studies also
allows determining a rating benchmark for each question. These benchmarks are used to evaluate the
environment under investigation $E$. This environment is assessed by a significant number of its occupants $B_s$
against the previous assessment of similar environments by their occupants $B_e$. All elements of this investigation
type can be changed. Even the perceptual, cognitive and affective appraisal of the environment $M^a$ changes
through for example education and learning of the occupants. The structure of the assessment system shown in
Fig. 6a reflects the multi-dimensional characteristic of human assessment of environments discussed at the
beginning of this paper.

Evaluation statements $E$ in such studies are usually displayed in tables, charts and with indices separately for the
dimensions of environmental assessment. Sophisticated multi-modal representations are not required for this
type of investigation as the expected behavior and actual measured behavior statements are pre-structured in a
form supportive for human reasoning through the design of the questionnaire (scope and structure).

For environmental assessment based on occupant surveys (of this type) the significance of the evaluation
depends on the availability of a sufficiently large database of similar studies in order to determine benchmarks
Therefore refinements processes $r_F$ and $r_r$ should not be triggered in repetitive studies unless significant changes in the focus of the investigation are required. The effects of situated and individual assessment through occupants in the environment are neutralized through statistic analysis of the votes collected from a significant number of occupants, while the assessment of building individual differences in the group of similar buildings is the purpose of the investigation.

![Diagram of environmental measurement process](image)

**Fig. 6.** Case 1: a. Development of the system, b. refinement and adaptation during application

### 4.3 Environmental measurement

#### 4.3.1 Description

Case 2 describes an improvement process under application of environmental measurement for building diagnostics in refurbishment projects for office environments. In this case the design object is available for investigation and development at design time. The example application is described in (Schwede, 2007a; Luther & Schwede 2005). The elements of the process are allocated as follows:

**Formulation**

- $F^p$: problem statements
- $F$: environmental assessment domains established through guidelines and performance standards
**M^f** models given in guidelines and performance standards for environmental assessment

**Be** target values given in guidelines and performance standards or set by the designer, consultant

**Analysis**

**I^S** change opportunities and constraints provided by structure, change capabilities and organizational and financial means

**S** office environment defined through physical, social and organizational properties

**C** climate, physical, social and organizational environment

**M^a** Measurement on-site with specialized equipment for the various evaluation domains. Modeling of the structure’s behavior is not required as it is measured directly in the physical world, although Change of the physical measurement set-up is possible.

**Bs** measurement results stated in the structure defined by the available measurement equipment

**Evaluation**

**M^e** measured environmental parameters Bs are compared to target values for environmental performance Be and processed with appropriate evaluation models in order to generate an evaluation statement E

**E** diagrams, tables and evaluative text sections

**I** plan how to progress the design

**4.3.2 Discussion: environmental measurement**

Fig. 7 shows the development of the components of a building diagnostic study under application of in-situ measurement. General function statements F are translated via assessment models M^f into a set of physical parameters \{Be\}, which are to be measured in the physical world in order to supply assessment models M^e with the necessary information Bs to generate evaluation statements E.

All elements but the physical world M^e can be adjusted. M^f and M^e is constraint through the available knowledge on environmental assessment and the available instruments \{Be\} to measure environmental performance Bs. The measurement scheme \{Be\} can be adjusted in order to generate a different dataset Bs.

The structure of the system shown in Fig. 7a reflects the integrated behavior of the physical environment discussed at the beginning of this paper.
In building diagnostic studies a comprehensive measurement scheme is conducted in order to identify performance shortcomings, malfunction, functional misfits and ineffective operation. The findings are sufficient to identify problem areas and to prioritize, which problem is to be addressed in more detailed investigations, but not necessarily useful as basis for design development. Therefore building diagnostic studies aim to trigger refinement process $r_f$ to specify the problem formulation in more detail but they don’t necessarily aim to trigger refinement process $r_1$ to improve the structure under investigation. After a diagnosis $E$ is conceived $r_f$ and possibly $r_e$ would be triggered to adjust the measurement scheme $\{Be\}$ and the evaluation model $M^e$ to the new problem formulation.

As the aim of a building diagnostic investigation is to identify the problem rather than to inform the solution of a specific problem the scope of the formulation model $M^f$ and the set of functions $\{F\}$ is initially kept broad. Also the scope of the measurement scheme $\{Be\}$ which transforms the actual behavior of the environment $M_a$ into the
dataset Bs is broad. In such building diagnostic studies a large amount of data is generated in Bs and a large number of models and target values which specify the expected performance Be is available.

For the measurement setup in the example case (Luther & Schwede, 2005) the dataset Bs is generated with specialized equipment for the measurement of various physical phenomena and is saved in together more than 400 files in txt-format, rtf-format, jpg-format and bmp-format with different column separator types and timestamp formats.

Although M\textsuperscript{s} and M\textsuperscript{f} are well-understood and developed to a high level all these files must be handled by hand, which make the data analysis and the evaluation cumbersome, expensive and error-prone with the result that the full benefit of the sophisticated (and expensive) measurement Bs and the highly developed evaluation scheme Be can not be achieved. Therefore M\textsuperscript{s} and the generation of E is identified as bottleneck in the application of environmental measurement for building diagnostics. Therefore refinement process r\textsuperscript{e1} is triggered.

Through F\textsuperscript{e} \& M\textsuperscript{e} a computer aided data evaluation system is developed (Schwede, 2007a), see Fig. 8. It is capable of reading the multiple data files of various file formats, generated during the measurement campaign, into its working memory. Data processing functions calculate physical parameters and evaluation functions on its basis. Reporting functions generate charts, tables and evaluative text sections, which are then saved in an automatically generated report document. Measured environmental performance can be reviewed in multiple modes. The report presents the original data and evaluation statements for quantitative and qualitative appraisal.

![Diagram](image)

**Fig. 8.** Implementation of a computer aided data evaluation system for building diagnostics

With this tool available new opportunities to present the available data in more informative modes and combinations arise and refinement process r\textsuperscript{e1} is triggered in order to improve the representation of evaluation statement E. Also process r\textsuperscript{e} is initiated as the form in which Bs was now available allows more functions to be assessed on basis of the available data. The following benefits can be achieved after improvement of M\textsuperscript{e} through the multi-modal data evaluation system shown in Fig. 8:
- rapid processing – allows shorter iteration time, it reduces the time to develop the design, it increases the number of possible iteration cycles, and it shortens the time between analysis, evaluation and refinement action, thereby it increases the adaptive character of the investigation (effective for all refinement processes),
- extended scope of the study (actioned through \( r_1 \)),
- processing of more complex evaluation models (actioned through \( r_3 \)),
- more modes of representation of evaluation statements (actioned through \( r_{e1} \)),
- integrated assessment of phenomena (actioned through \( r_{e2} \)),
- tracking of measurement errors (effective for \( r_a, r_{e1}, r_{e2} \)), and
- enforcement of structured investigation (effective for \( r_a, r_f \)).

4.4 Integrated simulation

4.4.1 Description

Case 3 describes the development of a system to support the improvement process under application of integrated and predictive computational simulation. In this case design object is not directly available for investigation and development. Design and performance of design are temporally detached. The example support system is described in depth in (Schwede, 2006a, b, 2007b).

**Formulation**

\[
\begin{align*}
\text{F} & \quad \text{problem statements} \\
\text{F} & \quad \text{environmental assessment domains established through guidelines and performance standards} \\
\text{Mf} & \quad \text{specified through models given in guidelines and performance standards for environmental assessment} \\
\text{Be} & \quad \text{target values given in guidelines and performance standards or set by the designer or consultant} \\
\end{align*}
\]

**Analysis**

\[
\begin{align*}
\text{I}^5 & \quad \begin{array}{ll}
3\text{-dimensional interface to place objects and activity datasets in a digital self-contained design space,} \\
\text{parametric specification of material properties, activity datasets and sensor locations}
\end{array} \\
\text{S} & \quad \text{office environment represented through a digital object model} \\
\text{C} & \quad \text{climate and physical represented through a digital object model and modeled activities} \\
\text{Ma} & \quad \text{universal and integrated digital representation of physical phenomena / simulation model} \\
\text{Bs} & \quad \text{simulated results stated in the structure defined by the simulation model}
\end{align*}
\]
Evaluation

The simulated environmental parameters Bs are compared to target values for environmental performance Be and processed with appropriate evaluation models in order to generate an evaluation statement E.

Diagrams, tables and evaluative text sections

Plan how to progress the design

4.4.2 Discussion: integrated simulation

Fig. 9 shows the development of the components of a building performance investigation under application integrated simulation of the physical phenomena. As in the previous case, general function statements F are translated via assessment models M f into a set of physical parameters {Be}, which are to be simulated in the simulation model M a in order to supply assessment models M e with the necessary information Bs to generate evaluation statements E. In this case the simulation model M e and the input data structures {Bs} and {Be} are fixed, while the other components in the process can be adjusted to the needs of the specific design task.

The structure of the system shown in Fig. 9a reflects the integrated behavior of the physical environment discussed at the beginning of this paper.
The project sets out to develop a universal and integrated representation of physical phenomena $M^a$ which can be applied for analysis of environmental quality in future office environments. The system also provides components for multi-modal representation of simulation results $B_s$ and evaluation statements $E$.

The term ‘universal’ is used in two ways. First, the support system can be applied following the changing demands of the supported design process, rather than being confined by the simulation models structure $M^a$ and second that questions which were not known, when the system was developed can be answered on its basis.

The term ‘integrated’ is used first to indicate that the simulation model’s capabilities $M^a$ can be accessed through multiple interfaces $I^S$, $I^F$ and $E$. The second meaning of ‘integrated’ refers to the internal highly integrated representation of various physical phenomena to simulate physical behavior realistically.

In difference to an open approach, suggested by Fischer and Scharff’s (2000), which puts the owner of investigated problems in charge of model development and modifications, the approach applied here is to
provide a closed model of physical behavior, which can not be modified by the user, but which is implemented
between open interfaces. This approach implies that the physical behavior can be universally represented through
physical laws and that it is possible to determine a reasonable level of representation of physical behavior for the
architectural domain, so that no manipulation of the simulation model at design time is required.

The development of the universal representation is shown in Fig. 9a. For the formulation of the physical core
model a large number of assessment models which represent the function statement have been analyzed under
application of physical laws in order to find a common set of physical parameters. It is presumed that required
assessment models to generate useful evaluation statements can be constructed through physical laws in the later
application of the model as shown on the right side of Fig. 9a.

The core model is implemented in a volume-based approach, which is based on the concept of a geometrically
and physically self-contained design space. In the digital model of this space geometric relations and physical
processes are defined through topology and physical laws, this allows that the design can be developed through
specification of geometry information, material information and a limited set of information, to represent
phenomena outside the scope of the model (active behavior, and boundary conditions). The concept of the self-
contained representation reduces the requirements posed by the computational modeling at design time by
calculating complex geometric relations and various aspects of physical behavior based on simple model
specification and automatic internal functions.

The universal applicability is then achieved through application of basic cubic elements, named congeneric cells.
The design space is dismembered into these cells across the geometric boundaries of the designed artifact. Each
cell is represented through a self-contained model of its physical state and the behavior of the material at its
location and it interacts with its neighboring cells through exchange of energy, moisture, air, CO₂ and possibly
other contaminates. This exchange takes place through the common sections between cells or via cell surface for
radiative transmission (heat radiation, light, sound). The physical state, calculated for each cell, is displayed
graphically. As the cells represent the materials of the designed artifact, the designed artifacts physical behavior
emerges through depiction of the simulated state and the properties of the cells as exemplified in Fig. 10. As
multiple properties and physical states can be displayed and various evaluation models can be processed on basis
of the calculated parameters the design object’s performance can be reviewed in multiple modes in form of false
color pictures. Additionally to the geometric graphical display (shown in Fig. 10), physical parameters specified
locations within the design space can be read out with virtual sensor objects and saved in data files and presented
in charts, tables and evaluative texts sections similar as depicted in Fig. 8 for case study 2.
5. CONCLUSIONS

This paper presents a framework for the development of design support systems including the components of the process and the activities of designing based on the notation of Gero’s FBS framework. The framework provides an overview over the tasks involved in developing effective support systems, it demonstrates the interrelations between the components and it allows to pin-point components in the process which require improvement, enhancement and augmentation in order to improve the application of the support system in the design practice.

The framework allows mapping specific representation types – multi-dimensional, integrated and multi-model representation – to the activities in the design process.

Through the framework the refinement processes for the adaptive development of the designed artifact and the development of design support systems are differentiated and formulated formally. One of these reformulation processes advances the design of the artifact another advances the formulation of the design problem, while eight reformulation processes develop the process of designing and the aids to support design activity. In order to link the refinement processes to the F, B and S formulation the evaluation statement E and the design intervention I is added to the set of elements.

While the developed framework is located in the external world (it describes the mechanics of design development under application of design support systems) the cognitive activities in the process of designing are

Fig. 10. Object and cell representation and multi-modal representation of physical behavior in a self-contained design space model

Fig. 9b shows the refinement processes to adapt the system. The function interface I_F, the structure interface I_S and the formulation model M_F and the evaluation model M_e can be changed in the course of the design process through the refinement processes r_F, r_S, r_F and r_e respectively. The analysis model M_a and the data structures for the behavior datasets B_s and B_e and the structure and context representation SC are fixed. Refinement process r_a is not available for model improvement in this case.
isolated in the reformulation process \( r_0 : E \circ I \rightarrow I \). This process involves creative design and situated decision making, it utilizes the designer’s experience and other types of knowledge. \( r_0 \) can be described for example through models as given in (Gero, 1990, 1996, Gero and Kannengiesser, 1996).

The framework model the adaptive character of the design process through isolation of cognitive processes in \( r_0 \) in a central position of the framework. This accounts for the fact that the human designer can take multiple approaches to advance the design. Taking \( E \) at a specific time in an on-going design process as problem statement for a cognitive design activity \( E \circ I \rightarrow I \) allows to simulate the shifting of the focus of the human designer in response to external representations. Therefore the representation and content of \( E \) is significant for the development of the design artifact.

Interesting for the application described in this paper are the implementations of \( I^F \), \( I^S \) and \( E \) as they are the interfaces between the external and the interpreted world. As stated in the introduction: reasoning about the designed artifacts can be best informed through multi-modal representation which presents the design in various modes with emphasis on different aspect of the structure, function, behavior or evaluation statements.

The represented found to represent aspects on the other side of the interface best is an integrated representation in case of the structure interface \( I^S \), a multi-dimensional representation in case of the function interface \( I^F \) and a combination of a multi-dimensional and an integrated representation in case of the evaluation statement \( E \).

At the end of the paper three examples of change processes are analyzed using the developed framework. All three aim to improve environmental quality in office environments but apply different environmental assessment methods and different types of representation for the various components in the process.

The first uses occupant surveys, the second applies environmental measurement and the third is developed to investigate environmental quality through integrated computational simulations. The discussion of the cases provides advice on effective representation and the techniques how to provide and to develop such representations in the context of practice relevant application cases. Through the case studies it is demonstrated that the developed framework is capable of supporting the systematic analysis of change design processes in order to develop systems to support design development effectively. The application of the framework in these case studies also demonstrates various modes of representation relevant for designing and the significance of their interplay for the design outcome in a dynamic design process.

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REFERENCES


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