Knowledge-Based Space-Use Analysis:
Shedding Light on Trade-Off Between Less Space and Better Use

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What is sustainable design?

Adapted from Valentine (2010), “Sustainability: The Pleasures + Treasures for Less”, Class material, CEE 215, Stanford University
Stanford University Space and Furniture Planning Guidelines

“The magnitude of these (lifecycle) costs makes it even more important for the University to use its space wisely and efficiently.”

“It is often said that the most sustainable building is the one that is never built. A major goal of the guidelines is to ensure that we build only the space that we need.”
Observed case: publishing company building

- Option 1
- Option 2
- Option 3
...

The company hesitated in making its decision.
Knowledge-Based Space-Use Analysis

Analyzing space-use without a computer-assistance

Many design options with many spaces

Conventional or manual space-use analysis is unable to predict, document, and communicate the space utilization with sufficient consistency, transparency, and efficiency.

- Limited time for project development
- Continuous changes
- Complex relationship

Many design options with many spaces
Desired qualities

• Consistency
  – The results of the analysis are always the same given the same input information.

• Transparency
  – The results of the analysis and the rationale for the results are explained visually to support the decision-making about design.

• Efficiency
  – The results of the analysis are immediately updated when clients or architects change any input information.
Even best space planning tools depend on manual space-use analysis.

Onuma Planning System (USA)

dRofus (Norway)

Roomex (Finland)
Intuitive goal: developing a computer-assistive space-use analysis

Develop design options

Many design options

User and activity information

Automated space-use analysis system

Efficiency
Consistency

Efficiency
Consistency

Transparency

Change space usage plan

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Research scope

- **Educational and office buildings**
- **User information:**
  - Users: end-users
  - Within the scope: Type of users, the number of expected users, preferences, priorities
  - Out of the scope: Individual users
- **User activity information:**
  - Within the scope: Type of activities, their functional needs
  - Out of the scope: Individuals’ personal needs
- **Space information:**
  - Within the scope: Space types, the number of spaces, the size of space types, equipment information
  - Out of the scope: Space location, geometry, aesthetics information
Overview of points of departure

Desired qualities:
- consistency,
- transparency
- efficiency

Prior work
- Architectural programming
- Post-occupancy evaluation
- Workplace planning

Knowledge representation and reasoning (KR&R) as a promising approach

Knowledge for applying KR&R in space-use analysis
- Building knowledge base
- Reasoning about knowledge base
- Visualizing analysis results

Gaps in knowledge and derived research questions
Prior work

- Architectural programming
  1. Survey literature
  2. Describe the users
  3. Develop performance criteria
  4. Consider options
  5. Prepare the space specification
  (Cherry, 1999)

- Post-occupancy evaluation
  - basis for the development of design guidelines and criteria for use in the planning of similar facilities
  (Preiser, 1995)
  - "Without a feedback loop, every building is, to some extent, a prototype"
  (Zimmerman and Martin, 2001)
Prior work

- Workplace planning (Pennanen, 2004)

Modification of information by a decision-maker (option generation)

Space information

User information

User activity information

Mapping of user activities onto spaces

Utilization computation by a computer

Input by an analyzer

Analysis results
## Prior work

<table>
<thead>
<tr>
<th>Desired qualities</th>
<th>Architectural programming(^1,2)</th>
<th>Post-occupancy evaluation(^3)</th>
<th>Workplace planning(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consistency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Representing input information systematically</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>- Formalized method to compute utilization as a metric</td>
<td>[ ]</td>
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<tr>
<td><strong>Transparency</strong></td>
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<tr>
<td>- Providing the rationale for project-specific space-use</td>
<td>[ ]</td>
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<tr>
<td>- Visualization of space-use analysis results</td>
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<tr>
<td><strong>Efficiency</strong></td>
<td></td>
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</tr>
<tr>
<td>- Automated mapping of activities onto spaces</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>- Automated computation of utilization</td>
<td>[ ]</td>
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</tr>
</tbody>
</table>

KR&R as a promising approach

Formality for computer-assistive analysis

Logical entailment of sound and complete knowledge

New knowledge

(what is believed)

Flexibility (adding new KBase or modify existing KBase)

• Assisted iterative refinement model (Bhatt and Freksa, 2010)

By an analyzer (human)

Building KBase

By a computer

Modifying KBase

Reasoning for Design Intelligence
(e.g., conceptual reasoning, hypothetical inference)

Spatial Design and Visualization Tool
(e.g., ArchICAD)

Reasoning about KBase

Visualizing results

Design Semantics
(conceptual, qualitative, multiperspective representation)

convergence

design feedback
(e.g., analyse design requirements)

design
(e.g., floor plan)
Building KBase

- Building Information Model as space representation

- Construction activity representation (Darwiche et al., 1989; Aalami et al., 1998; Akinci, et al., 2000; Staub-French et al., 2003; Mourgues et al., 2008; Dong 2012)


- User profiles (Cherry, 1999; Shen et al., 2012)
“Five editors edit a book once a day. It is an individual work and takes two hours on average. This activity requires a workstation in the office, preferably a whole room with quiet conditions. The company would like to satisfy the preference because editors are key employees in the publishing industry.”

- <CARS> tuple (Akinci et al., 2002)

Different concepts and properties needed

Different specialization of <spatial requirements> needed

Component

Action

Resources (labor, equipment, material)

Spaces (hazard space, labor crew space, equipment space, protected space)
“Five editors edit a book once a day. It is an individual work and takes two hours on average. This activity requires a workstation in the office, preferably a whole room with quiet conditions. The company would like to satisfy the preference because editors are key employees in the publishing industry.”

- User activity model (Pennanen, 2004)

Limited formality in describing user activities (e.g., designation)
Reasoning about KBase

• Rule-based mapping approach

IF Space 1 contains a positive adjacency with space 2
AND Space 2 contains the same daylighting requirements as Space 1
AND Space 2 has an available side to place space 1
THEN Place space 1 adjacent to space 2

(Chinowsky, 1991)


By an analyzer (human)

Building KBase

Modifying KBase

Visualizing results

By a computer

A computer system

Analysis results

Design Semantics
(conceptual, qualitative, multiperspective representation)

Reasoning for Design Intelligence
(e.g., conceptual reasoning, hypothetical inference)

Spatial Design and Visualization Tool
(e.g., ArchiCAD)

Convergence

design feedback
(e.g., analyse design requirements)

design
(e.g., floor plan)
Visualizing results

- Spatio-temporal visualization of performance (Akbas et al., 2007)

Gap: knowledge to process KBase to analyze and visualize space-use

By an analyzer (human):
- Building KBase
- Modifying KBase

By a computer:
- Reasoning about KBase
- Visualizing results

Design Semantics
(conceptual, qualitative, multiperspective representation)

Reasoning for Design Intelligence
(e.g., conceptual reasoning, hypothetical inference)

Spatial Design and Visualization Tool
(e.g., ArchiCAD)

Input? Output? Control? Mechanism?
Research questions

To apply KR&R in automating space-use analysis,

- How can user activities be represented for use in space-use analysis?
  - My answer: a user activity ontology

- How can the space-use analysis process be formalized to automatically analyze and visualize space-use?
  - My answer: a formalized process for automated space-use analysis
Research methodology

State-of-the-practice

State-of-the-theory

Concept formalization

Identify characteristics of user activities

Define concepts for space-use analysis

Formalize relationships among the concepts

Develop an ontology for user activities

Process formalization

Develop space mapping rules

Develop visualization format

Define input, output, control, and mechanism for each functional step

(Noy and McGuiness, 2001)

Validation study

- 3 case studies
- 8 hypothetical tests

(UML)

(IDEF0)
Concept formalization

- Identify characteristics of user activities
- Define concepts for space-use analysis
- Formalize relationships among the concepts
- Develop an ontology for user activities

Literature review, observation

→

Expert survey
(14 experts with 8.5 years of experience in space-use analysis)

C1: Some users require a space with more than minimum requirements for their activities.

C2: Some activities require having a designated space. (Pennanen, 2004)

C3: Some activities require occupying whole rooms while others need part of rooms.

C4: Some activities are conducted in a specifically named space while others are conducted in any space with certain conditions.

C5: Some atypical activities also require a space. (Cherry, 1999)

- Level of agreement on every characteristic: 4+ over 5
- No additional characteristics suggested other than the five
Concept formalization

- Identify characteristics of user activities
- Define concepts for space-use analysis
- Formalize relationships among the concepts
- Develop an ontology for user activities

Mapped if all spatial requirements of an activity are met by a space or equipment.

Equipment

Spaces

Spatial requirements

Activities

Action

<UAS> tuple

Product

Organization

Utilization

open time

activity load

Policy on utilization implication

Form

Behavior

Function

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Concept formalization

- Identify characteristics of user activities
- Define concepts for space-use analysis
- Formalize relationships among the concepts
- Develop an ontology for user activities

Legend

<table>
<thead>
<tr>
<th>Class</th>
<th>Cardinality:</th>
</tr>
</thead>
<tbody>
<tr>
<td>property</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0..*</td>
</tr>
<tr>
<td>Association</td>
<td></td>
</tr>
</tbody>
</table>

**UML class diagram**

- **C1**: More than minimum requirements
- **C2**: Designated space
- **C3**: Whole vs. part of a room
- **C4**: Certain conditions
- **C5**: Atypical activity

- **ImportantUser**
  - **RegularUser**
  - **User**
    - `userNumber`
  - **Action**
    - `actionName`
    - `groupSize`
    - `duration`
    - `spaceCriteria`
  - **UserActivity**
    - `activityName`
    - `action`
    - `constraints`
    - `preferences`
  - **SpatialRequirements**
    - `reqName`
    - `spaceName`
    - `spaceType`
    - `designation`
  - **WholeRoomUseRequirements**
    - `spaceCondition`
    - `spaceNumber`
    - `spaceMinSize`
  - **EquipmentUseRequirements**
    - `equipName`
    - `equipCondition`
    - `equipNumber`
    - `equipMinSize`
## Concept formalization

- Identify characteristics of user activities
- Define concepts for space-use analysis
- Formalize relationships among the concepts
- Develop an ontology for user activities

### Example of <Spatial requirements>

<table>
<thead>
<tr>
<th>Property</th>
<th>Cardinality</th>
<th>Value type</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Requirements name</td>
<td>{1:1}</td>
<td>String</td>
<td>N/A</td>
</tr>
<tr>
<td>Space name</td>
<td>{0:*}</td>
<td>Instance</td>
<td>Space</td>
</tr>
<tr>
<td>Space type</td>
<td>{0:*}</td>
<td>Instance</td>
<td>Space type</td>
</tr>
<tr>
<td>Designation</td>
<td>{1:1}</td>
<td>Boolean</td>
<td>True, False</td>
</tr>
<tr>
<td><strong>Properties of whole room use requirements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space condition</td>
<td>{0:*}</td>
<td>Instance</td>
<td>Conditions</td>
</tr>
<tr>
<td>Space number</td>
<td>{0:1}</td>
<td>Integer</td>
<td>Positive</td>
</tr>
<tr>
<td>Space minimum size</td>
<td>{0:1}</td>
<td>Float</td>
<td>Positive</td>
</tr>
<tr>
<td><strong>Properties of equipment use requirements</strong></td>
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</tr>
<tr>
<td>Equipment name</td>
<td>{0:*}</td>
<td>Instance</td>
<td>Equipment</td>
</tr>
<tr>
<td>Equipment condition</td>
<td>{0:*}</td>
<td>Instance</td>
<td>Conditions</td>
</tr>
<tr>
<td>Equipment number</td>
<td>{0:1}</td>
<td>Integer</td>
<td>Positive</td>
</tr>
<tr>
<td>Equipment minimum size</td>
<td>{0:1}</td>
<td>Float</td>
<td>Positive</td>
</tr>
</tbody>
</table>
“Five editors edit a book once a day. It is an individual work and takes two hours on average. This activity requires a workstation in the office, preferably a whole room with quiet conditions. The company would like to satisfy the preference because editors are key employees in the publishing industry.”

editorsEditing:TypicalActivity [user -> editors, action -> editBook, ratio -> 1.0, frequency -> 1.0, constraints -> cons2, preferences -> pref2].
editors:ImportantUser [number -> 5].
editBook:Action [groupSize -> 1, duration -> 2.0, spaceCriteria -> 4.5].
cons2:EquipmentUseReq [space -> officeArea, equipment -> workStation, minSize -> 4.5, designation -> False].
pref2:WholeRoomUseReq [number -> 1, minSize -> 15, conditions -> quiet, designation -> False].

in F-Logic (Angele et al., 2009)
Process formalization

1. Develop space mapping rules
2. Develop visualization format
3. Define input, output, control, and mechanism for each functional step

For all activities,

- Activity requiring designated spaces
  - Yes
  - No

Find space

- Number of spaces
  - Event quantity*:
    - >0: Divide spaces and designate
    - =0: Designate
    - <0: Designate and record shortage

Map

*Event quantity*: the number of groups for a given activity by dividing users by the group size of the activity
Process formalization

- Develop space mapping rules
- Develop visualization format
- Define input, output, control, and mechanism for each functional step

Implication of the utilization (policy on utilization)

- • : No wait
- • : Adequate
- • : Inconvenient
- • : Infeasible

Based on Pennanen (2004) and Cherry (1999)
Knowledge-Based Space-Use Analysis

Facts

- ontology for space-use analysis
- data collecting templates
- space mapping heuristics
  - metrics necessary for the mapping

Process formalization

- Develop space mapping rules
- Develop visualization format

Rules

- Define input, output, control, and mechanism for each functional step

Notation (IDEFO):

- Input
- Function
- Output
- Mechanism
- Control
Validation summary

Validation plan:
• Experimental group: knowledge-based space-use analysis (KSUA)
• Control group: workplace planning (Pennanen, 2004)
• Metrics: desired qualities (consistency, transparency, efficiency)

<table>
<thead>
<tr>
<th>Case studies</th>
<th>H publishing company, Korea</th>
<th>Cygnaeus High School, Finland</th>
<th>Y2E2 Building, USA</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># of space types</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td># of user groups</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td># of user activities</td>
<td>4</td>
<td>5</td>
<td>13</td>
<td>22</td>
</tr>
<tr>
<td># of KBase</td>
<td>31</td>
<td>49</td>
<td>65</td>
<td>145</td>
</tr>
<tr>
<td># of hypothetical tests</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>

- Power: improved consistency, efficiency, and transparency
- Generality: three cases (2 educational and 1 office) representing different space types, user groups, and user activities
The Y2E2 Building case

- Representing user activities

100% of activities (13) were represented in a computer-interpretable form based on the proposed ontology.

Gathering user and their activities info.
- Observation and interview
- Enrollment information

Representing user activities in F-Logic (Angele et al., 2009)

User activity ontology
The Y2E2 Building case

- Formalized space-use analysis process

65 Facts: project-specific
(5 user types, 13 activities, 9 space types)

undergradsMeetingForClass:TypicalActivity[user -> undergrads, action -> haveMeeting, ratio -> 1.0, frequency -> 0.2, constraints -> cons3, preferences -> pref3].

33 Rules: project-independent

?SP252[activity -> ?ACT252] :-
  ?ACT252:TypicalActivity,
  ?SP252:NonOccupiableSpace[equipped -> ?EQSET252],

A space-use analysis prototype developed in Flora-2 Visualizer
The Y2E2 Building case

• Space-use analysis results: Activity-space mapping diagram

1-1: gradsHavingClass
1-2: undergradsHavingClass
2-1: gradsMeetingForClassWithComputers
2-2: undergradsMeetingForClassWithComputers
3-1: gradsMeetingForClass
3-2: undergradsMeetingForClass
4: groupMeetingForResearch
5-1: gradsStudying
5-2: undergradsStudying
6: facultyWorking
7: staffWorking
8: researchersWorking
9: facultyMeeting

computerCluster
classRoom
smallConferenceRoomWithComputer
conferenceRoomWithComputer
privateOffice
sharedOffice
openOffice
smallConferenceRoom
largeConferenceRoom

9 space types

0.99

26 links generated automatically

13 activities
The Y2E2 Building case

- Space-use analysis results: Utilization summary, Activity-loaded space

Legend:
- ACT1: facultyMeeting
- ACT2: gradsMeetingForClass
- ACT3: groupMeetingForResearch
- ACT4: undergradsMeetingForClass

conferenceRoomWithComputer (utilization = 0.58)

Size: 250 sf.

0.23 hrs 1.48 hrs 2.03 hrs 0.87 hrs

open time: 8 hrs

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• Hypothetical tests

First option (test 1):

Hypothetical tests prevent undergraduate students from using small conference rooms and letting them find any other conference rooms for their study on top of the first option.

Second option (test 2):

Goal: Keeping utilization of all spaces ‘no wait’ or ‘adequate’.

Number: 2 → 3

Size: 546 ft² → 389 ft²

preventing undergraduate students from using small conference rooms and letting them find any other conference rooms for their study on top of the first option.
• First option

1-1: gradsHavingClass
1-2: undergradsHavingClass
2-1: gradsMeetingForClassWithComputers
2-2: undergradsMeetingForClassWithComputers
3-1: gradsMeetingForClass
3-2: undergradsMeetingForClass
4: groupMeetingForResearch
5-1: gradsStudying
5-2: undergradsStudying
6: facultyWorking
7: staffWorking
8: researchersWorking
9: facultyMeeting

computerCluster
classRoom
smallConferenceRoomWithComputer
classRoom
conferenceRoomWithComputer
privateOffice
sharedOffice
openOffice
smallConferenceRoom
largeConferenceRoom

0.99 -> 0.82

Mapping (24 links) updated automatically
• Second option

1-1: gradsWithClass
1-2: undergradsWithClass
2-1: gradsWithMeetingForClassWithComputers
2-2: undergradsWithMeetingForClassWithComputers
3-1: gradsWithMeetingForClass
3-2: undergradsWithMeetingForClass
4: groupMeetingForResearch
5-1: gradsWithStudying
5-2: undergradsWithStudying
6: facultyWorking
7: staffWorking
8: researchersWorking
9: facultyMeeting

computerCluster
classRoom
smallConferenceRoomWithComputer
generalRoom
conferenceRoomWithComputer
privateOffice
sharedOffice
openOffice
smallConferenceRoom
largeConferenceRoom

0.82 -> 0.68

: deleted links
: added links

Mapping (24 links) updated automatically
Validation of power

3 Case studies with 8 hypothetical tests

<table>
<thead>
<tr>
<th>Workplace planning</th>
<th>Knowledge-based space-use analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency</td>
<td></td>
</tr>
<tr>
<td>• Informal, incomprehensive representation of activity</td>
<td>• Formal, comprehensive representation of activity</td>
</tr>
<tr>
<td>• Ad hoc-based mapping</td>
<td>• Rule-based mapping (same output given an input)</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
</tr>
<tr>
<td>• Time-consuming in adjusting the mapping when input changes</td>
<td>• Rapid update in adjusting the mapping when input changes (0.016 sec.)</td>
</tr>
<tr>
<td>Transparency</td>
<td></td>
</tr>
<tr>
<td>• No visual control</td>
<td>• Visualization of results</td>
</tr>
</tbody>
</table>
Contribution to knowledge

Application of KR&R in space-use analysis

Ontology for representing user activities (UAS tuple)

Formalized space-use analysis process

Space 1 contains a positive adjacency with space 2
Space 2 contains some daylighting requirements as Sun
Space 2 has an available side to face space 1
Space 1 adjacent to space 2
Contribution to practice

Decision support for building less space with better use

Less crowded, more flexible use

Iterative design refinement

Less cost, more sustainable

Environment

Automation of space-use analysis

Desired qualities

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Architectural programming</th>
<th>Post-occupancy evaluation</th>
<th>Workplace planning</th>
<th>Automated Space-Use Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representing input information</td>
<td>Red</td>
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<td>Yellow</td>
<td>Green</td>
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<tr>
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<tr>
<td>analysis results</td>
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<td>Yellow</td>
<td>Yellow</td>
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<tr>
<td>onto spaces</td>
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<td>Automated computation of</td>
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<td>Yellow</td>
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<tr>
<td>utilization</td>
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</tbody>
</table>
Limitations and assumptions

• Limitations
  – Domain: Office and educational buildings
  – Limited scope regarding user / activity / space information
  – No consideration of time varying and stochastic features

• Assumptions:
  – Spatial requirements of a user activity should be entirely satisfied by a space to trigger the mapping between the activity and the space.
  – A single activity has only one action.
Future research: Accurate space-use analysis

Calibration method of “up-to-date” space-use analysis

Accurate space-use analysis
  • Accuracy

Measurement and analysis of real space-use data

A framework for knowledge-based space-use analysis
  • Consistency
  • Transparency
  • Efficiency

Current space-use analysis

Continuous upgrade of space-use analysis
  • Time-varying
  • Stochastic features
  • More input factors
  • Space mapping rules
Future research: High-resolution performance-based design

Ontology for representing user activities

Current performance analysis methods

“High-resolution” performance analysis

By Modeling interface

Modifying analysis method

Automated space requirements update

Activity-based energy consumption analysis
Acknowledgement

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Knowledge-Based Space-Use Analysis

Thank you!

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