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analyses of **Spatial Topology** **2012 – 13**

Funded by the Construction Engineering Research Laboratory – U.S. Army Engineer Research and Development Center (CERL- ERDC)

Graduate Student: Varvara Toulkeridou

Understanding spatial relations on building components plays an important role in decision-making during the process of designing a building. Moreover, querying spatial relations in an existing design solution can facilitate evaluation of the design in terms of meeting specific criteria and requirements. Common questions include

- "Is the bedroom adjacent to the bathroom?"
- "Are the electromechanical spaces separated from the user spaces?"
- "What is the shortest egress from this room to the exit?"

Such queries refer to *spatial topology* requirements.

Problem Statement

Building information models offer a promising infrastructure for spatial reasoning. Beyond explicitly representing building components, their properties and geometric characteristics, BIM, additionally, represents basic topological relationships among building components. However, current central model management servers, which mediate between user and BIM, are not based on certain spatial semantics of particular attributes and relationships and therefore, information stored in these models cannot be interpreted, adequately, to infer spatial relations.

Objectives

The objective of this project is to identify, extract and represent spatial relationship information embedded in BIM architectural models, in order to facilitate certain spatial topology queries. Collectively, these queries can serve as an evaluation tool of existing 3d building models against standard building criteria. We chose to work in the context of Industry Foundation Classes (IFC) to ensure that the resulting spatial topology representation is independent of the BIM 3d modeling software used. To facilitate complete and efficient spatial query and reasoning, three individual objectives were set:

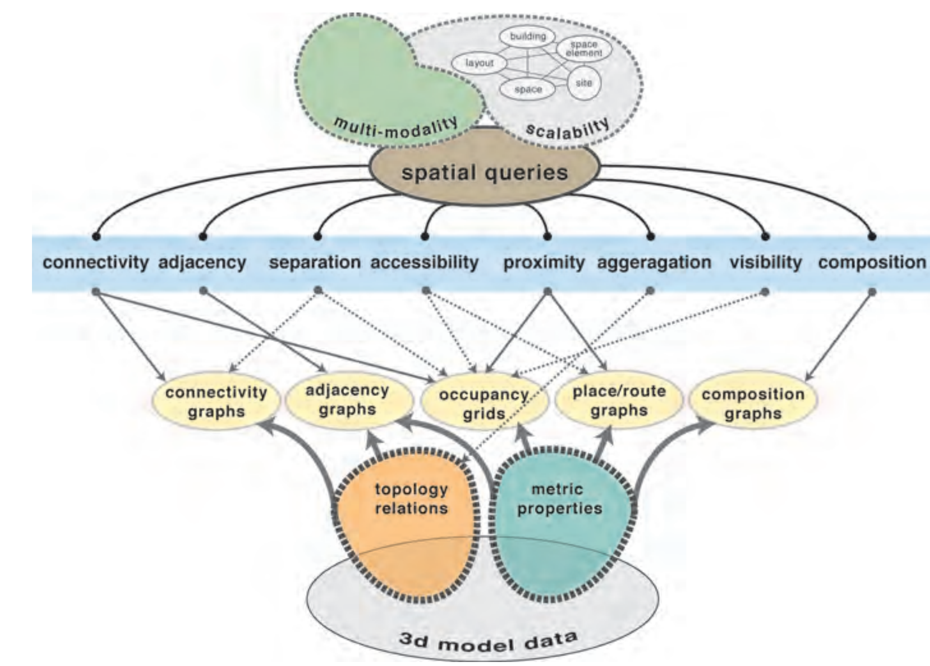
- Identifying the type of data that is embedded in an IFC tree hierarchy
- Determining how effectively this data can be extracted
- Determining how effectively the data can be restructured into a tool offering representational flexibility

Steps

1. We examined precedent research focusing on spatial reasoning and query, stemming from the domains of computer-aided design, geospatial information systems and artificial intelligence.
2. We identified key dimensions and gaps that characterize the research solution space explored. The result of our evaluation is that there is need to address, complementarily, both the geometric properties and topology relations embedded in the three-dimensional data

model and a need to implement a representation model that supports scalability and multimodality.

3. We evaluated public agency design criteria documents of three different building types: a. Family housing; b. Brigade operations complex and brigade & battalion headquarters; and c. Military medical facilities. From this evaluation we identified common classifications of spatial requirements referring to connectivity, adjacency, separation, accessibility, proximity, aggregation, visibility and composition relations.
4. We classified spatial relationship data that is embedded in an IFC tree hierarchy, either explicitly or implicitly, to infer the spatial relations identified in step 3.
5. We implemented a Java application that parses an IFC model, extracts relevant spatial topology data and generates spatial topology graphs for connectivity, adjacency, composition and containment. The application's user interface displays the graph representations and allows the user to perform specialized queries. The implementation is intended to be representationally flexible; that is, a user can switch easily across levels in the IFC tree or between spatial relations.
6. The behavior of the final prototype is tested and demonstrated against example cases taken from three IFC models: a. a Duplex Apartment; b. an Office building; and c. a Medical clinic.



Legend

spatial relations identified in building design criteria documents (UFC)

graph data structure types identified in the surveyed literature

topology data explicitly or implicitly stored in the 3d model

metric data stored in the 3d model

3d model data; in the context of the literature review is either IFC-based data or shape files

denotes links identified in the literature review from a type of spatial relation to the type of graph structure that can answer a relevant query
arrow head: points to the type of graph structure
arrow end: starts from the type of spatial relation

denotes suggested links from a type of spatial relation to a type of graph structure or a type of data that can answer a relevant query

denotes links of the type of data required to the resulting graph type
arrow head: points to graph type
arrow end: starts from the data type

Figure. Graphical representation of the key dimensions of the surveyed literature and the classification of spatial requirements identified across the three design criteria documents

Contributions

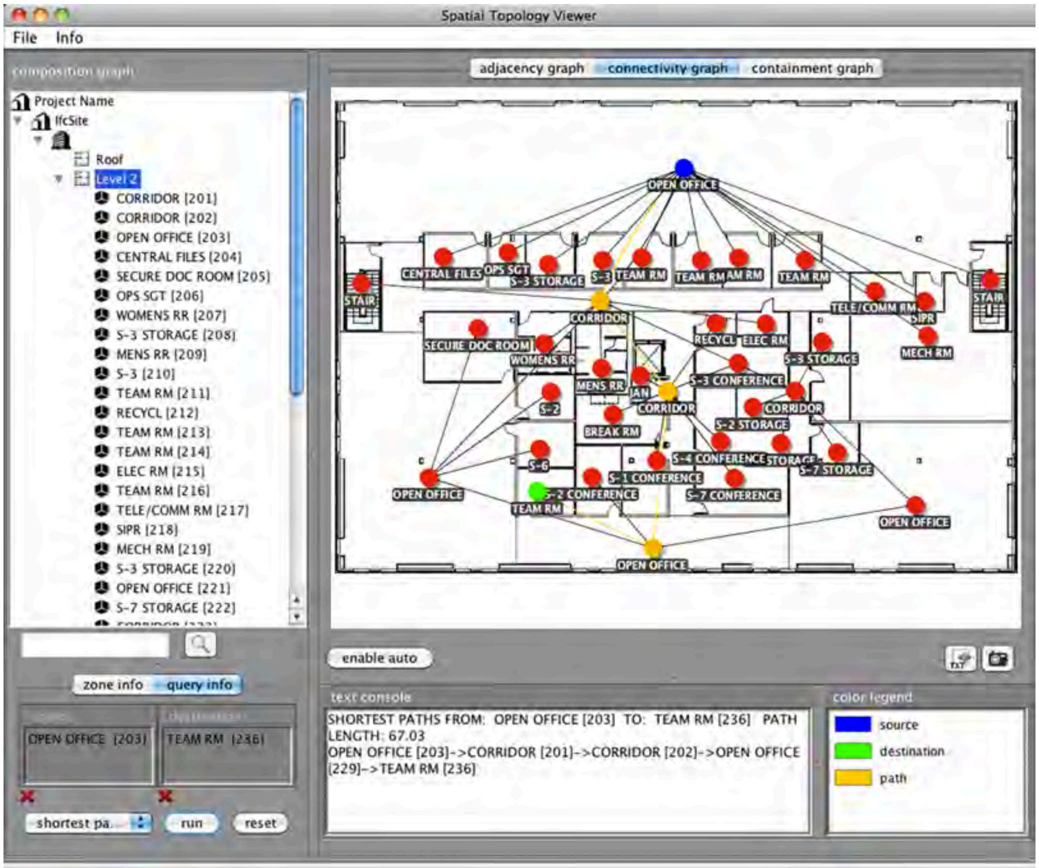


Figure. The spatial topology viewer's user interface

- **IFC data classification for deriving spatial topology relations**

We provide a data classification that outlines the type of data to be extracted from an IFC 3d model for deriving certain types of spatial topology relations, namely adjacency, connectivity, containment and composition. The classification is based on an investigation of how IFC conceptualizes space, how it breaks space down into its basic entities and how it defines relationships among those entities. This classification provides the basis for further developing an IFC Model View Definition for deriving spatial topology information.

- **Highlight the limitations of the IFC for deriving spatial topology relations and provide the ways of addressing them**

We show that with the spatial topology data stored in an IFC model, it is not always adequate to extract consistent spatial topology relations unless geometric properties of building components are complementarily addressed.

- **Developed and demonstrated a proof-of-concept working prototype**

We suggest and design algorithms to aggregate the identified IFC data and implement them into a proof-of-concept prototype. We confirm the implementation's correct and consistent behavior by testing it on the three IFC 3d models.

- **Highlight importance of an implementation that supports multimodality and scalability**
- **Classification of the types of spatial topology relations involved in spatial requirements across three different design criteria documents**

Publications

- Ramesh Krishnamurti, Varvara Toulkeridou, Tajin Biswas (2014) Communicating semantics through model restructuring and representation, *Building Information Modeling: BIM in Current and Future Practice* (eds Karen Kensek, Doug Noble) Wiley [ISBN 978-1118766309] [In press]

standardising **Data Exchange** for **LEED analysis** **2010 – 11**

Funded by US Army Core of Engineers Construction Engineering Research Laboratory (CERL-ERDC)

Graduate Students: Tajin Biswas, Tsung-Hsien Wang and Varvara Toulkeridou

Background

This research explores the augmentation of the Construction Operations Building information exchange (COBie) – a lightweight building information model, as an intermediary data structure, to bridge between requirements of the Leadership in Energy and Environmental Design (LEED) rating system and a building information model. Development of a general framework for data sharing and information management for LEED assessments is illustrated through an implementation of a prototype using functional databases.

Objectives

- Analyze data requirements for filling a total of 69 LEED 2.2 templates from Construction Operations Building Information Exchange (COBie), standardized Building information Modeling format used by the Army Core of Engineers.
- Classify missing data, create a relational database for supplementing 55% of the missing data and augment the data structure for implementation in the prototype application.
- Create LEED XML schema for filling LEED HTML templates
- Translate LEED queries into a computable form to provide a semi-automated process for LEED assessments and evaluation for designers using COBie.

Problem

Sustainable design assessment requires information, which is aggregated from different phases of a building design, and evaluated according to criteria specified in a 'sustainable building rating system.' In the architecture engineering and construction (AEC) domain much of the necessary information is available through open source data standards such as Industry Foundation Classes (IFC). However, no single standard that provides support for sustainability assessment completely suffices as a data structure.

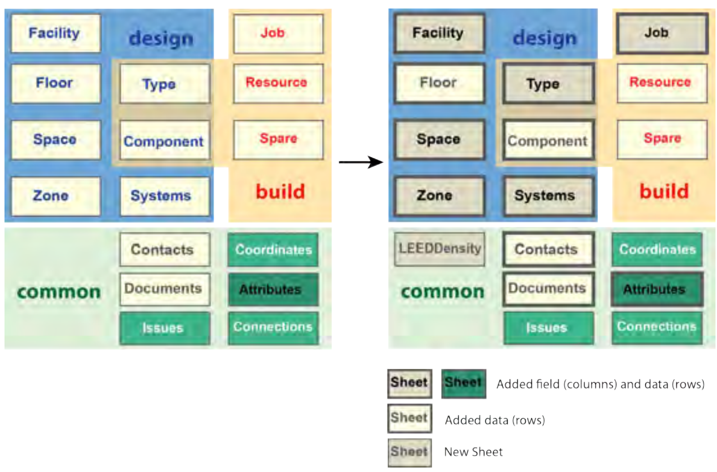


Figure. From COBie to COBie plus: Illustrating the augmentation of COBie for LEED (Source for the left side: East, E.W., Construction Operations Building Information Exchange (COBie), http://www.wbdg.org/resources/cobie.php)

COBie is based on the Industry Foundation Class (IFC) model. One of the formats COBie adopts is a spreadsheet format; we use this because it offers a structure that can be easily used, extended and augmented, in particular to work with a functional database prototype. In this research the data structure is referred to as ‘COBie Plus’, which is a COBie model that has been modified by augmented information needed for sustainability assessment.

The COBie+ data model is assessed according to the rules, and LEED templates are accordingly filled with available information. At any stage in a project, as project information changes, users can update the COBie + model and generate new or updated LEED submission templates.

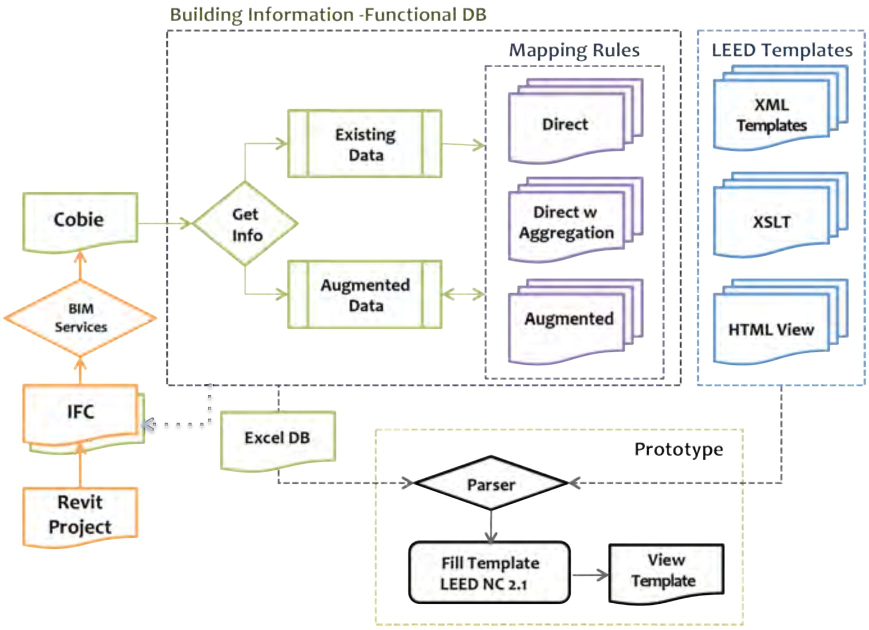


Figure. Data sharing for sustainability assessment workflow

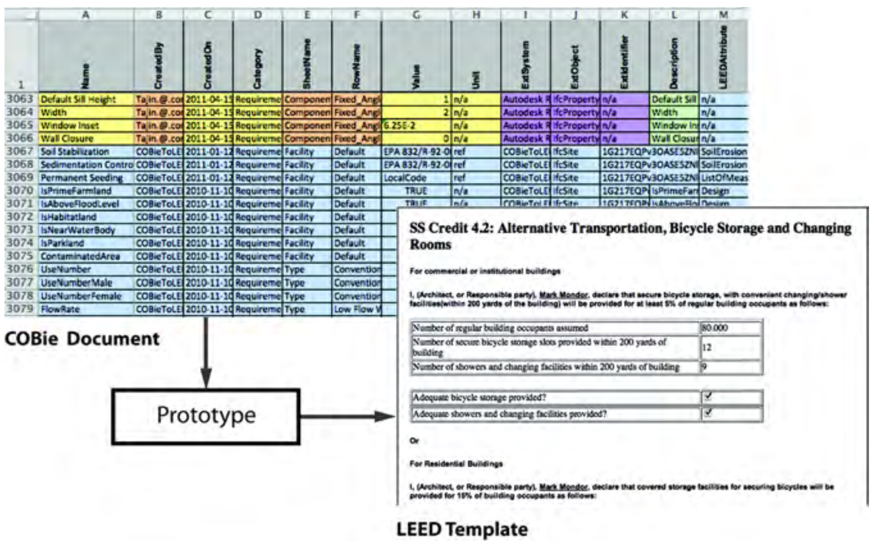
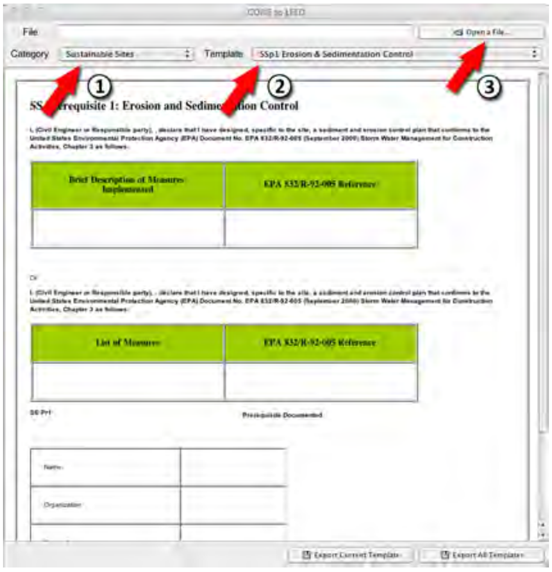
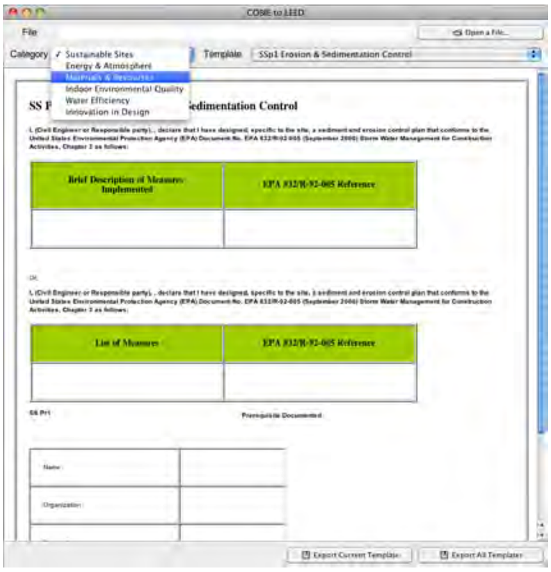


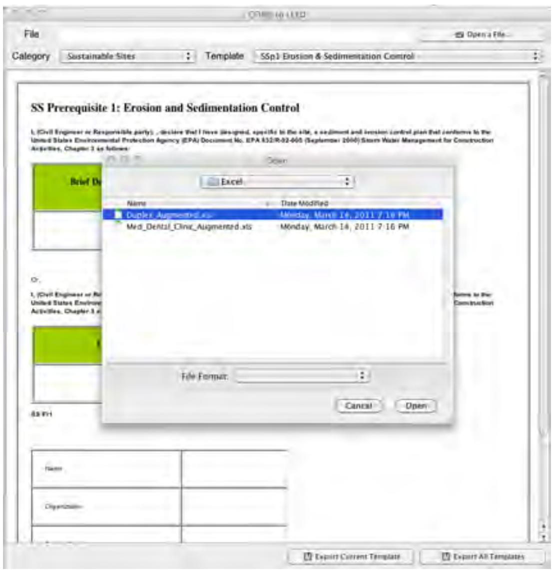
Figure. Data sharing for sustainability assessment by the prototype



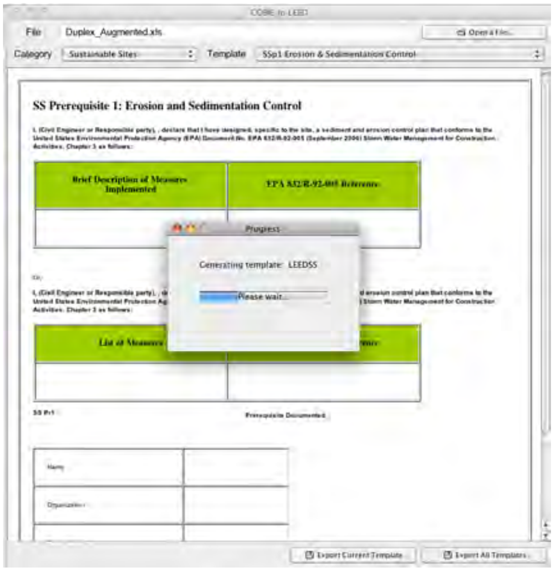
a Prototype user interface



b Selecting LEED category of templates



c. Selecting COBie file



d. Filling templates from COBie file

Publications

- Ramesh Krishnamurti, Varvara Toulkeridou, Tajin Biswas (2014) Communicating semantics through model restructuring and representation, *Building Information Modeling: BIM in Current and Future Practice* (eds Karen Kensek, Doug Noble) Wiley [ISBN 978-1118766309] [In press]
- Tajin Biswas, Ramesh Krishnamurti (2012) Data Sharing for Sustainable Building Assessments, International Journal of Architectural Computing, Volume 10, Issue 4, December 2012, 555-574. DOI: http://dx.doi.org/10.1260/1478-0771.10.4.555
- Tajin Biswas, Tsung-Hsien Wang, Ramesh Krishnamurti (2012) Data Sharing for Sustainable Assessments: Using Functional Databases for Interoperating Multiple Building Information Structures, *Beyond Codes and Pixels* (eds T Fischer, K De Biswas, J J Ham, R Naka, W X Huang) pp 193-202. Proceedings of the 17th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA), Chennai, 25-28 April 2012

Parametric Panelization for Constructible Surfaces 2009 –

With my doctoral student, Tsung-Hsien Wong

The objective

To explore parametric constructive strategies to achieve a more aesthetic, attractive, fabrication-friendly structures when developing freeform architectural designs.

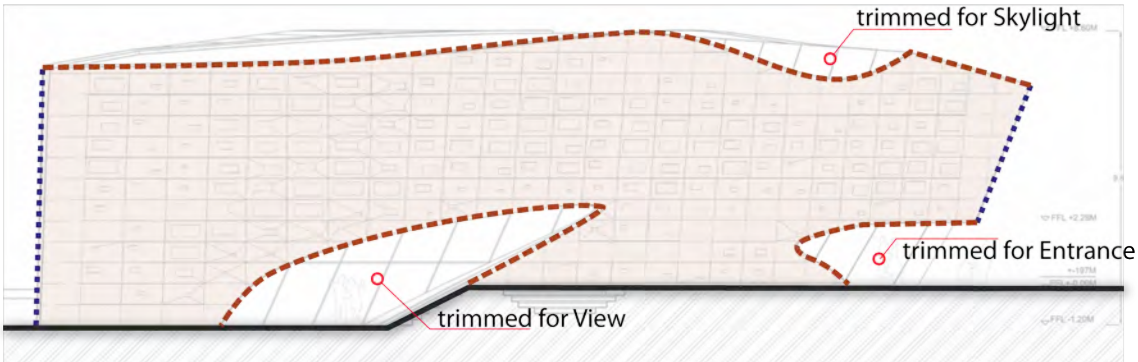
The goals

Parametric Framework: To go beyond current limitations in isoparametric analyses by developing a framework in which procedures for segmenting freeform surfaces with discrete constructible components can be encapsulated.

Boundary Optimization: To explore irregular boundary conditions at given surfaces so that propagation of the pattern-based panel components can be effectively re-designed and other design intentions, for instance, panel patterns, size, or panelization direction can be effectively re-examined.

The basic problem

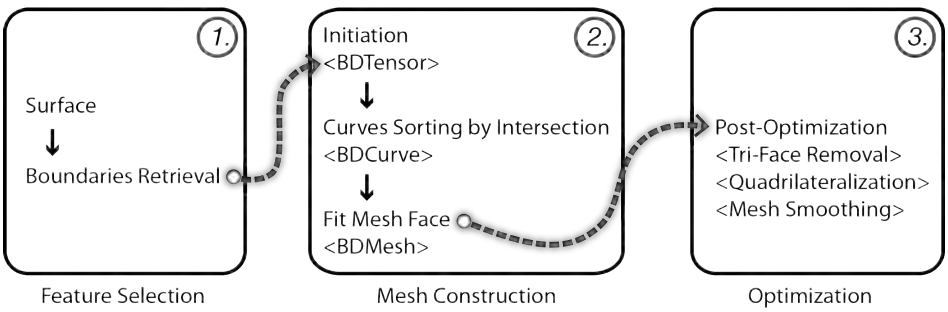
A freeform surface trimmed/cut for various purposes



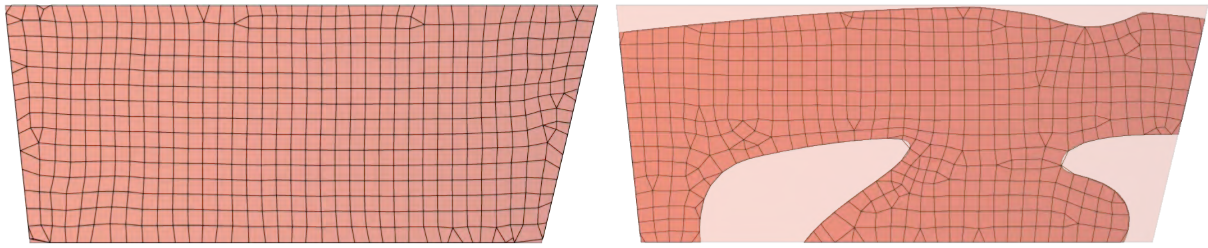
To produce architecture – skin/frame/joint

Geometrically to create panels based on a mesh element, such as a triangle, quadrilateral, hexagon, etc.

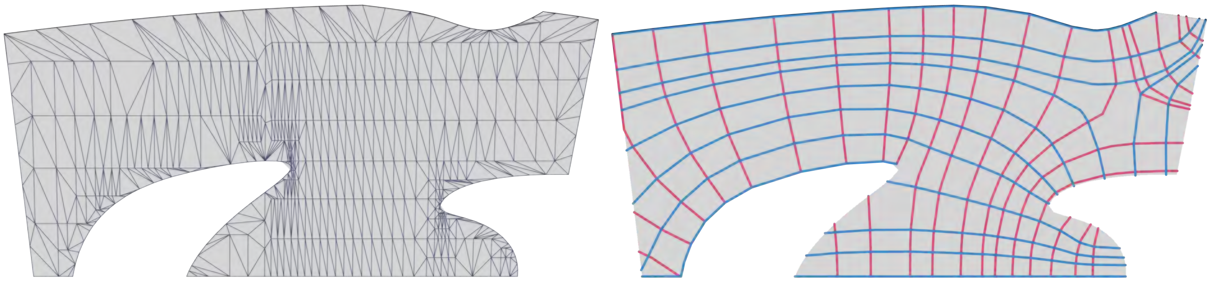
Solution workflow



Step 1- boundary driven quad mesh generation

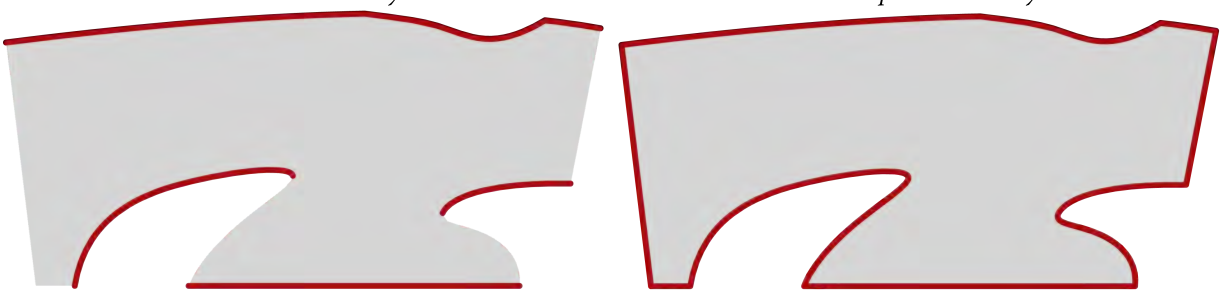


Packing direction based on x- and y-axes. As the complexity of the boundary grows—that is, with more trimmed boundaries, the number of irregular mesh elements such as triangles or non-uniform clusters increases.

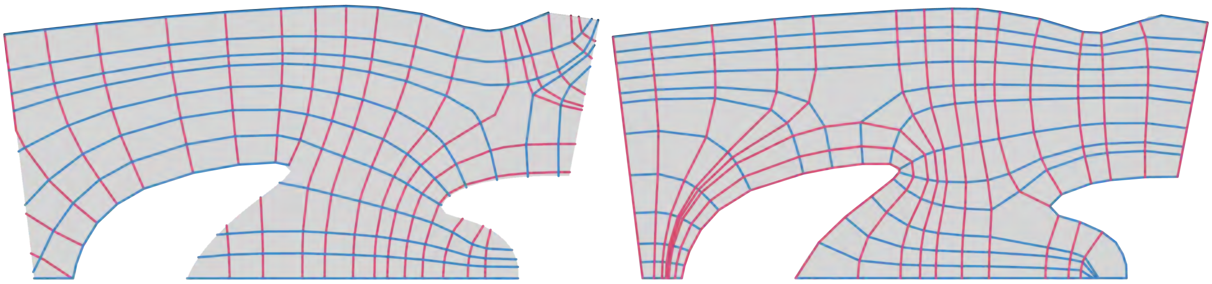


The tensor field exploited is organized as a 3-dimensional lattice to define local packing size and direction.

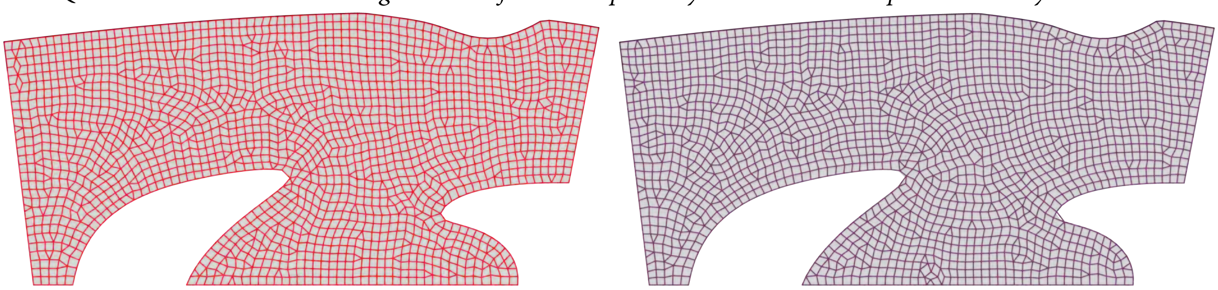
Partial boundary *Complete boundary*



Intermediate Mesh Generation from the Tensor Field

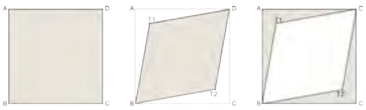


Quad-dominant bubble mesh generation for both a partially selected and complete boundary conditions



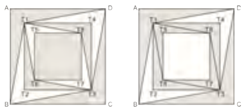
Step 2 - parametric panelization - example of an L-system based procedural approach

Inspired by a Calatrava design



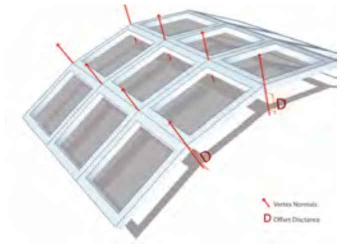
Reconstruction rules

+

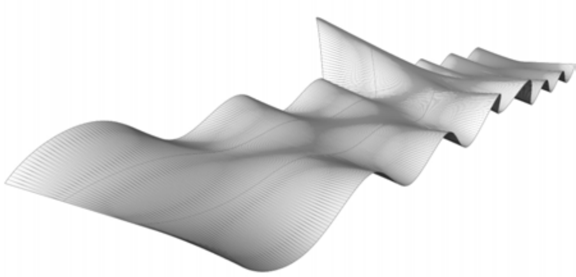


Fenestration rules

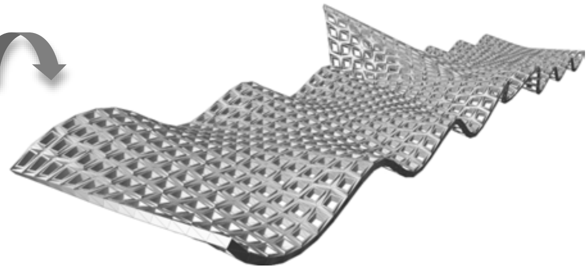
+



Offset rule

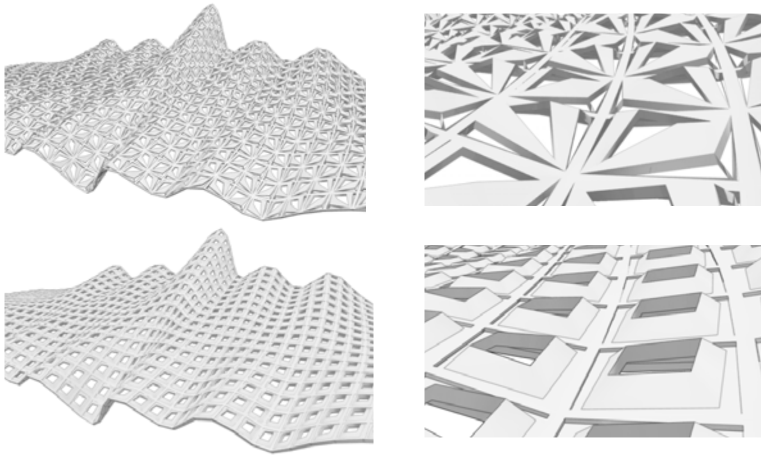


Freeform surface

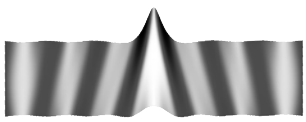


Tessellated panelized surface

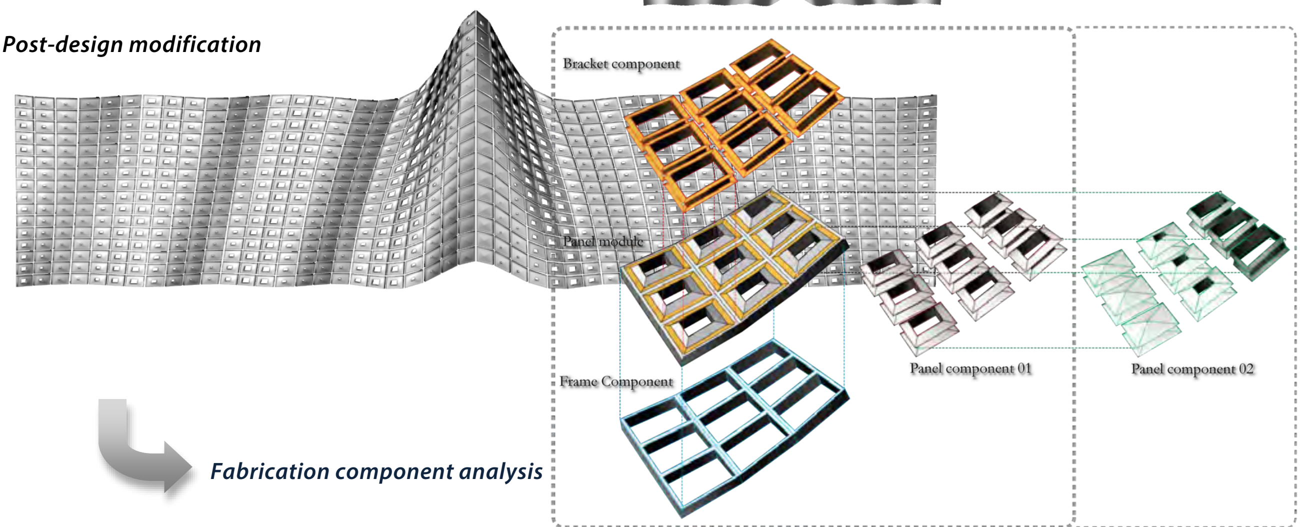
Parametric panel generation



Lighting simulation plotted on a monochrome scale from black to white and applied to the tessellated surface



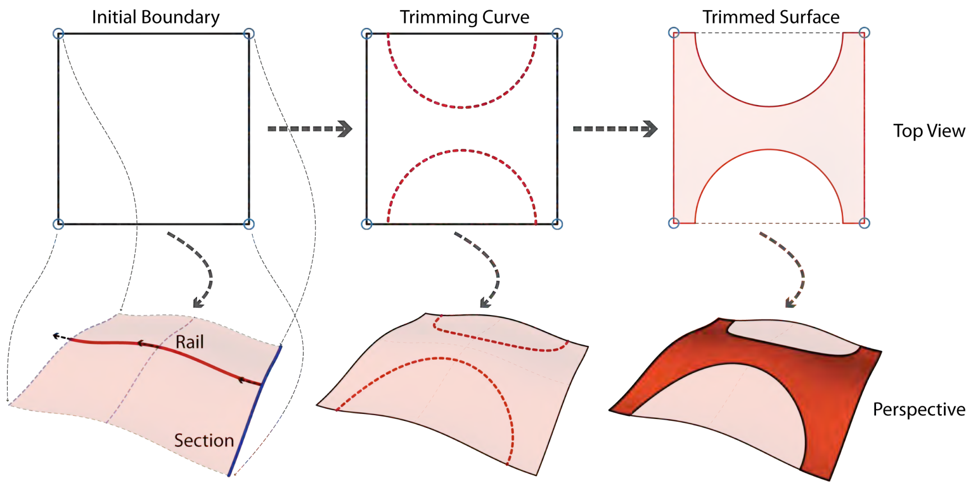
Post-design modification

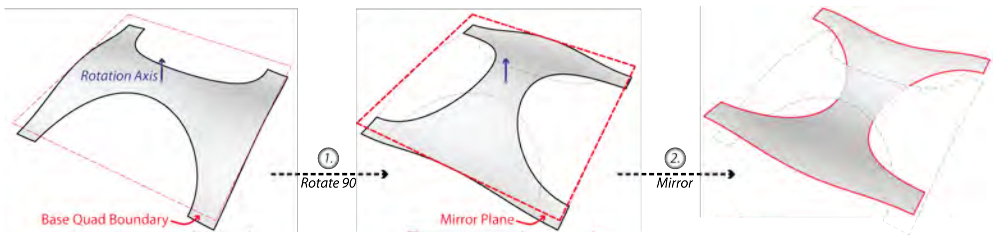


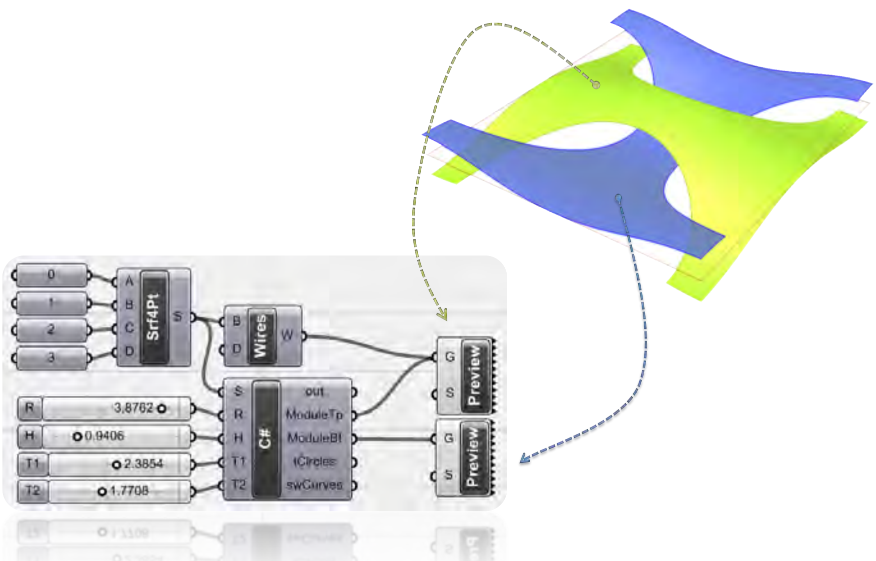
Fabrication component analysis

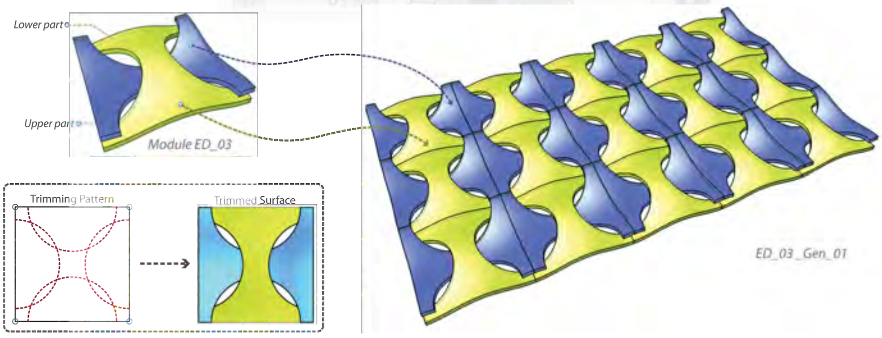
Step 2 – panelizing by interwoven patterns – *inspired by Erwin Hauer designs*

Interwoven patterns can be created by trim and transformation of a basic mesh element.

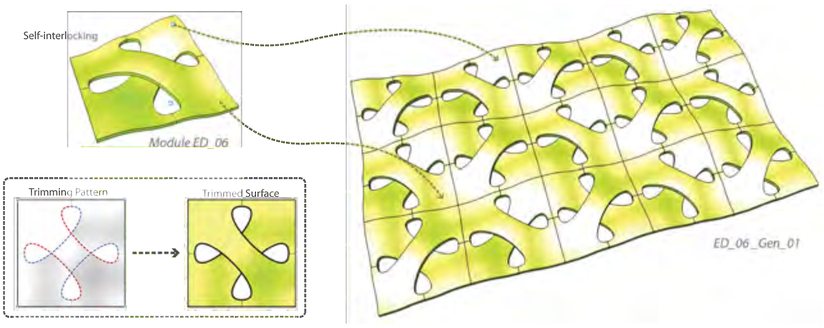


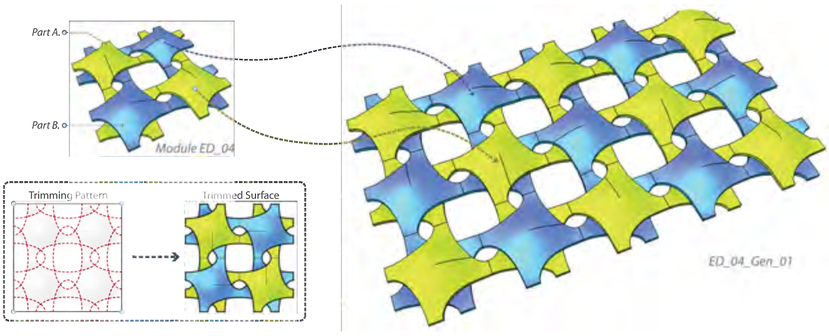


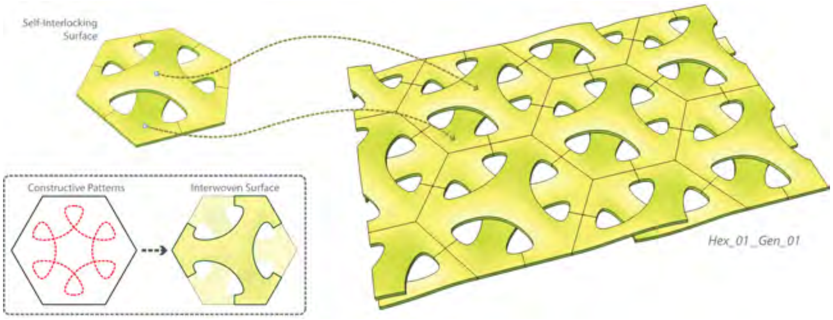


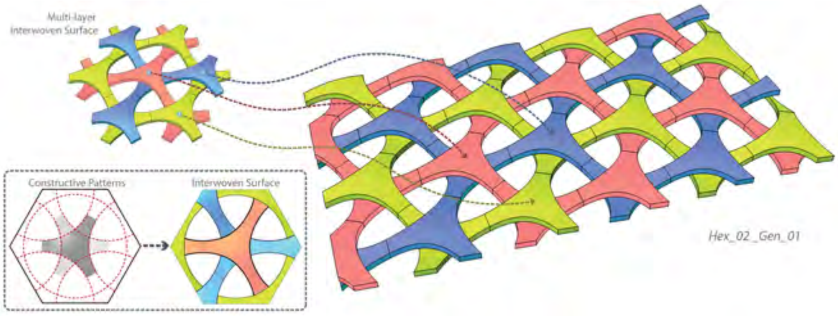


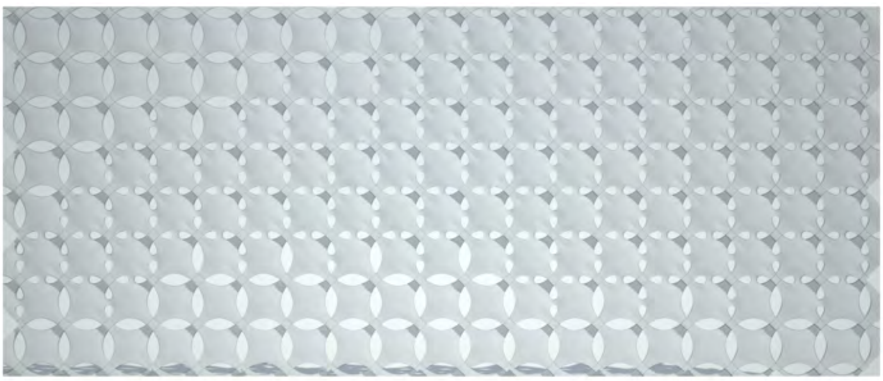
Examples of quad- and hexagon-based interwoven patterns



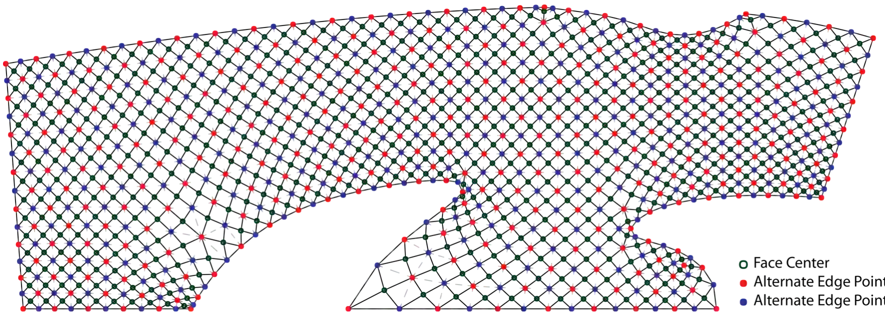


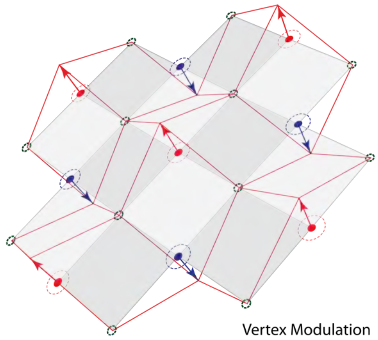




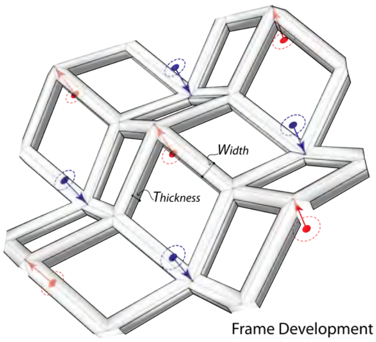


Step 2- semi-regular panelization

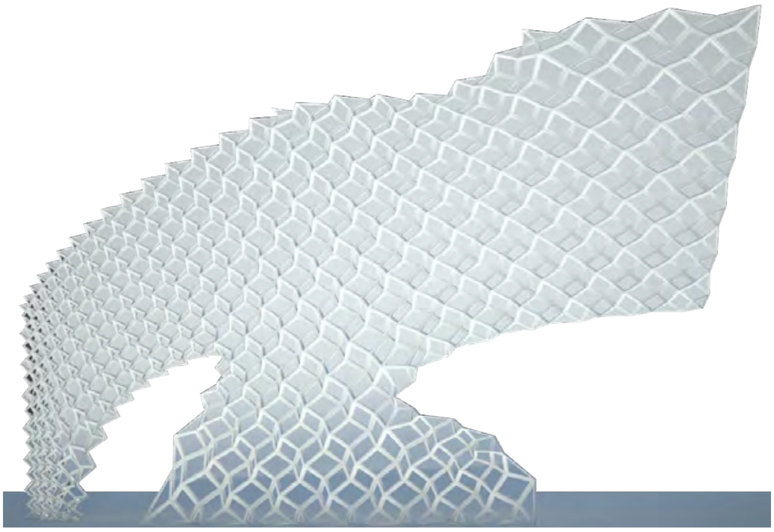


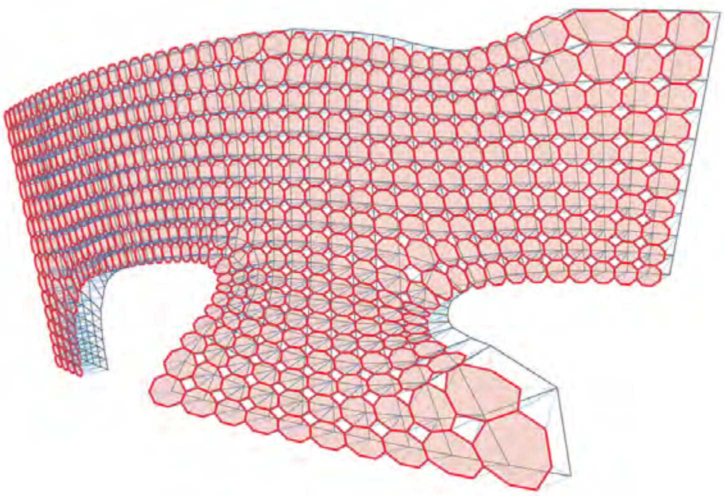


Vertex Modulation



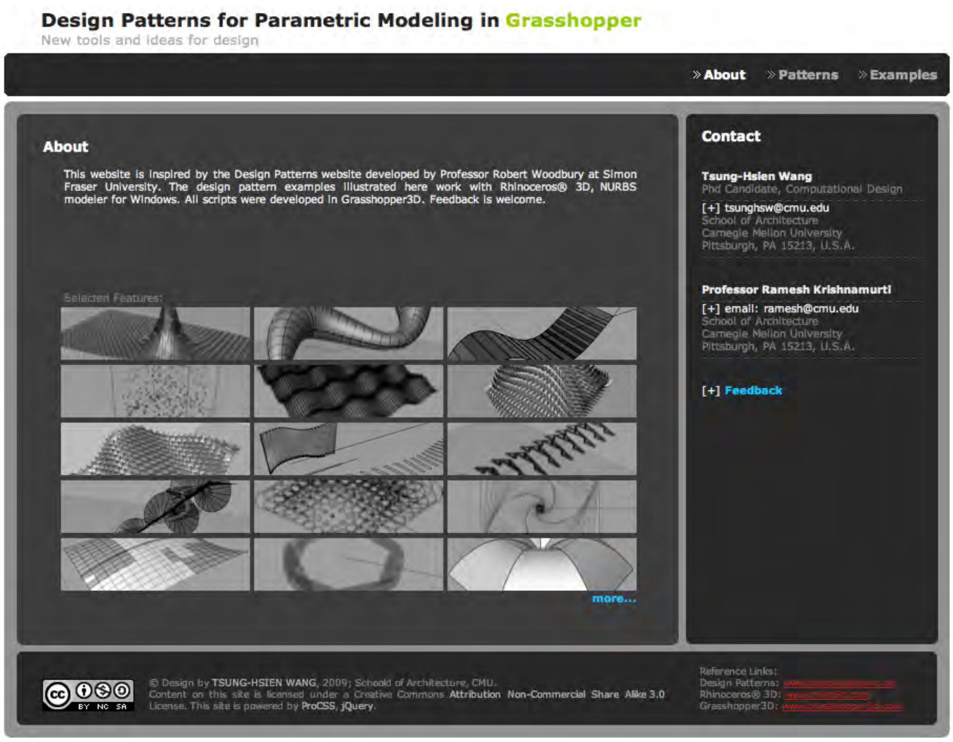
Frame Development *by* Mesh Edges





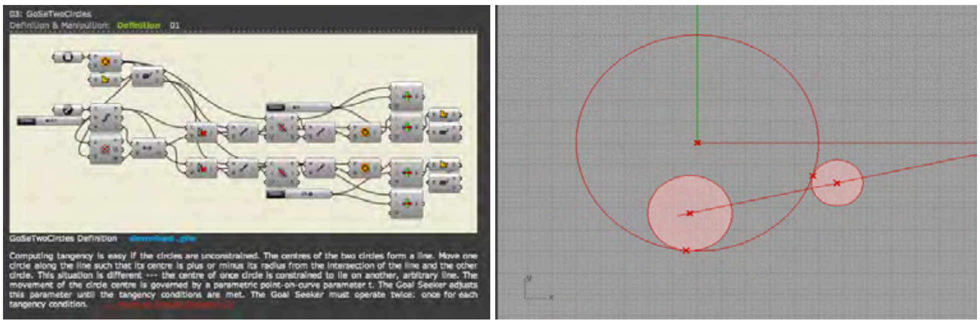
Design Patterns

Are inspired by Rob Woodbury's work on design patterns, www.designpatterns.ca, which provides the parametric modeling community with well-crafted examples of reusable code. The work of Woodbury and his researchers is based in Bentley's Generative Component. We have carried out a similar exercise based in Rhino and Grasshopper: www.andrew.cmu.edu/org/tsunghsw-design/ .



Design patterns are examined in my course on parametric modeling, http://www.andrew.cmu.edu/course/48-724/

Goal seeking pattern

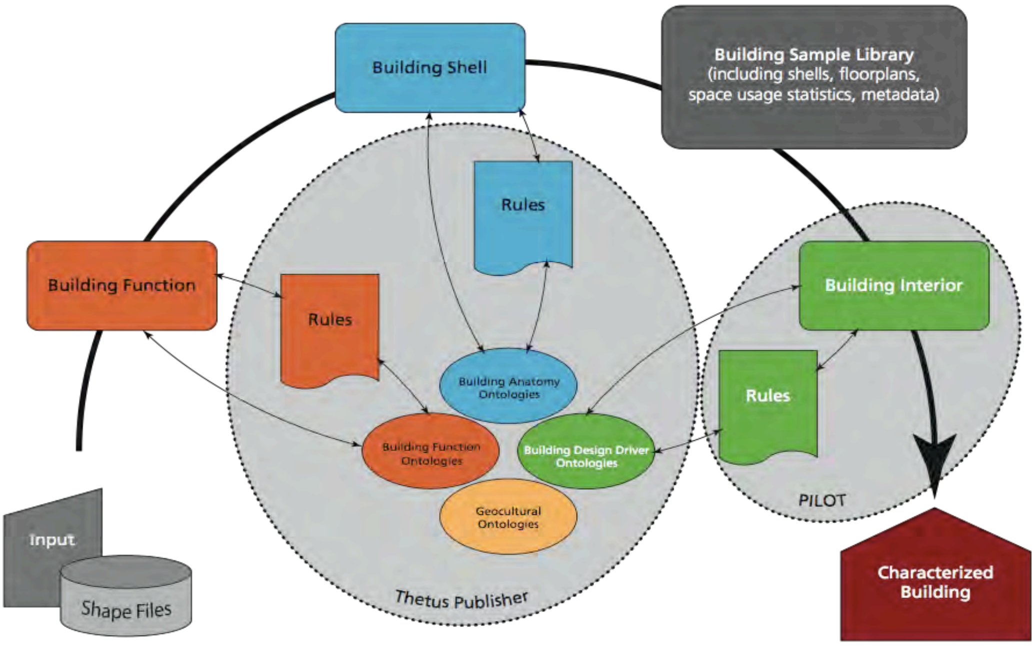


3D recursion pattern

pilot + autopilot: (**auto**matic) **p**rising of **i**nterior **l**ayouts **o**ver building **t**ypes **2007 – 09**

Funded by the US Army Corps of Engineers CERL-ERDC.

A collaborative project



A problem of tactical significance in urban operational situations

Target location within a building prior to human intervention.

There are two essential aspects to this problem: firstly, the spatial dimension: generating possible layouts; and secondly, the reasoning dimension: estimating the likelihood of any particular layout. We concentrated on the former, although due consideration was given, incrementally, at increasing levels of technical detail, on the relationship and feedback between the spatial and reasoning components.

A Queen Anne house

Segmented image

We have developed a method for rule-based generation of possible layouts for the interior of a building, implementing the method as a prototype for layout generation, formulated as two tasks:

i) Develop a mechanism to convert prior knowledge into sets of rules, recorded in a database;

ii) Generate possible interior layouts using shape rules augmented by inputting known features.

The short-term assumption, at a minimum, was the availability of a 2.5D model, presumed derived from image data, augmented with associated external features, which include building footprint plus height, and other obtainable building features, such as number, size, and position of windows, paths, etc. The longer-term goal is to automate the system by extracting both the 2.5D model and building features from photo images of the target building.

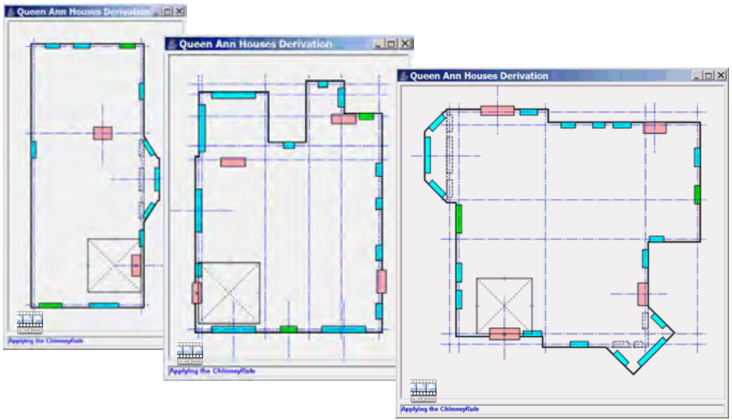
Buildings share several characteristics, which translate into spatial features. Buildings can be characterized in different ways — by *type*; by *architect or designer*; by *urban city*; by *style*; by *construction*; by *culture*; and so on. Based on such characterizations, we can formulate spatial rules in a systemic fashion by means which building designs and layouts can be generated.

Shape grammars have been shown to be extremely useful and adept in these endeavors

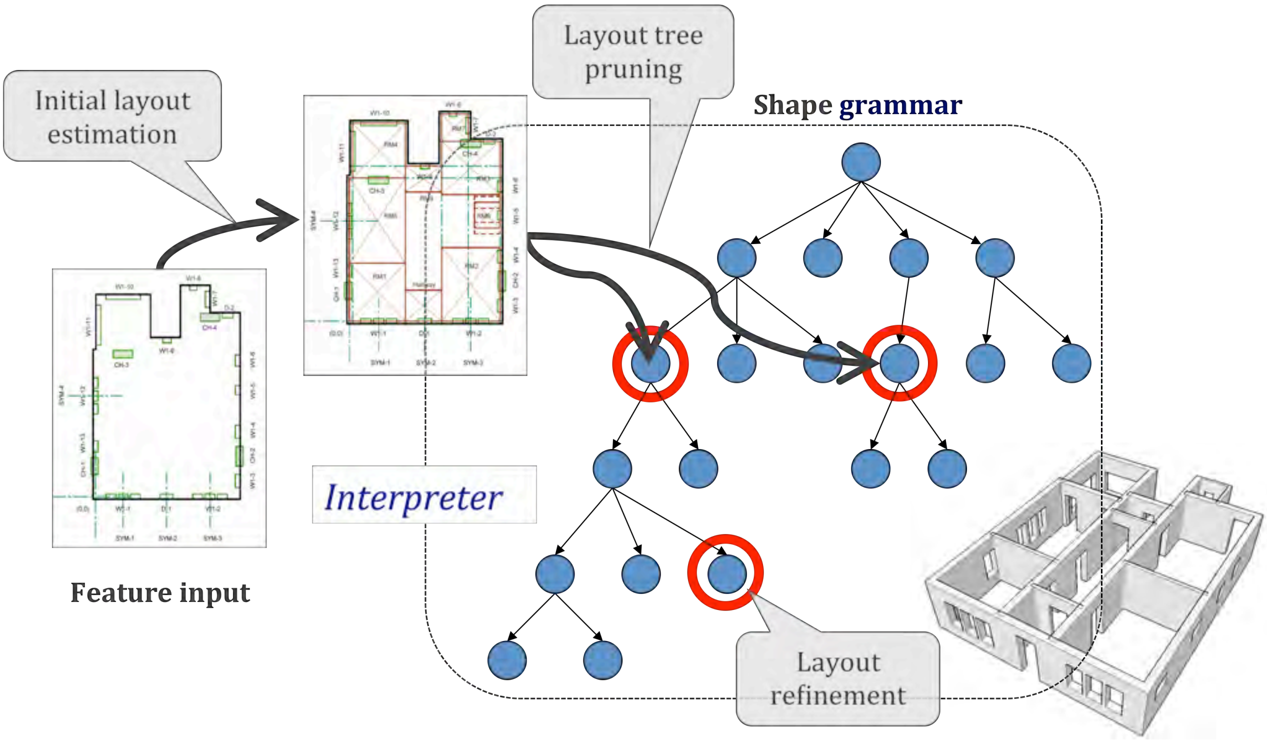
Approach

Input: *Footprint annotated with exterior features*

- *Initial layout estimation using constraint satisfaction*
- *Final layout estimation using shape rules*

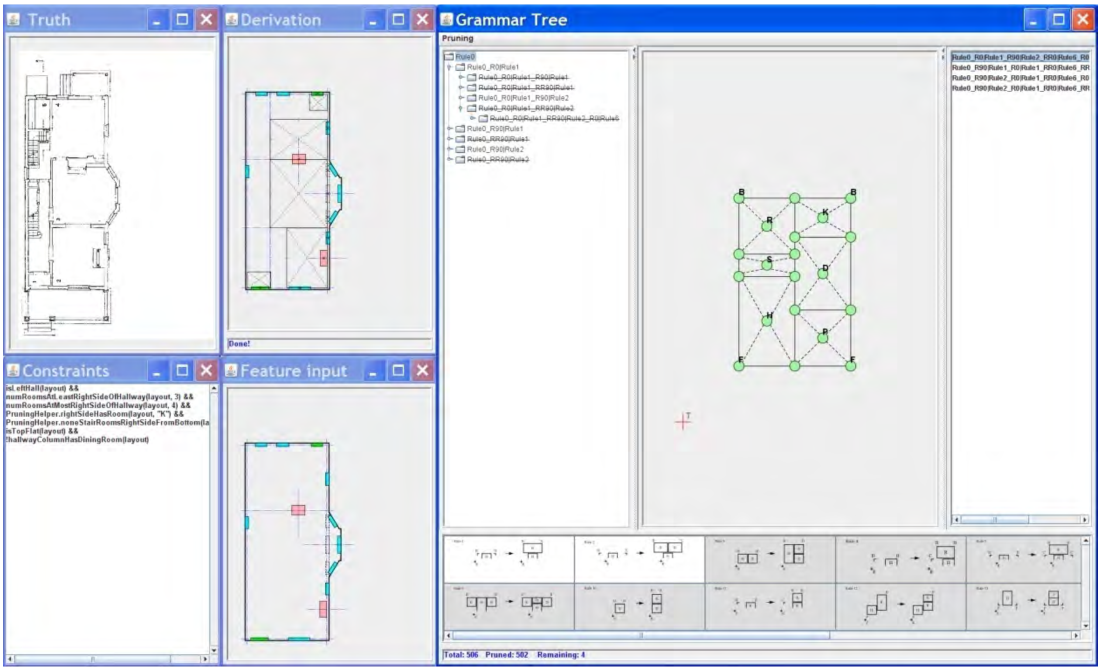


Initial layout estimation using constraint satisfaction on a number of different footprint shapes

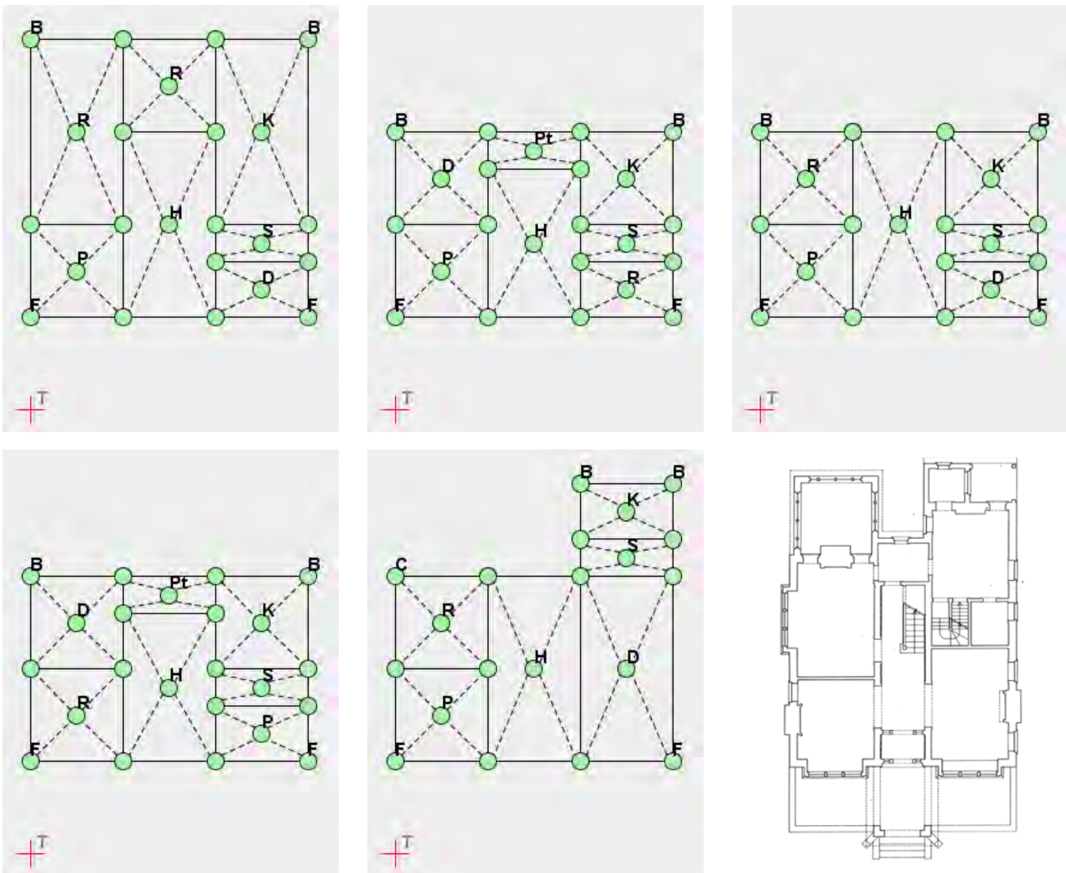


Test Case: The Queen Anne House

The Queen Anne House layout determination constraint satisfaction and grammar prototype



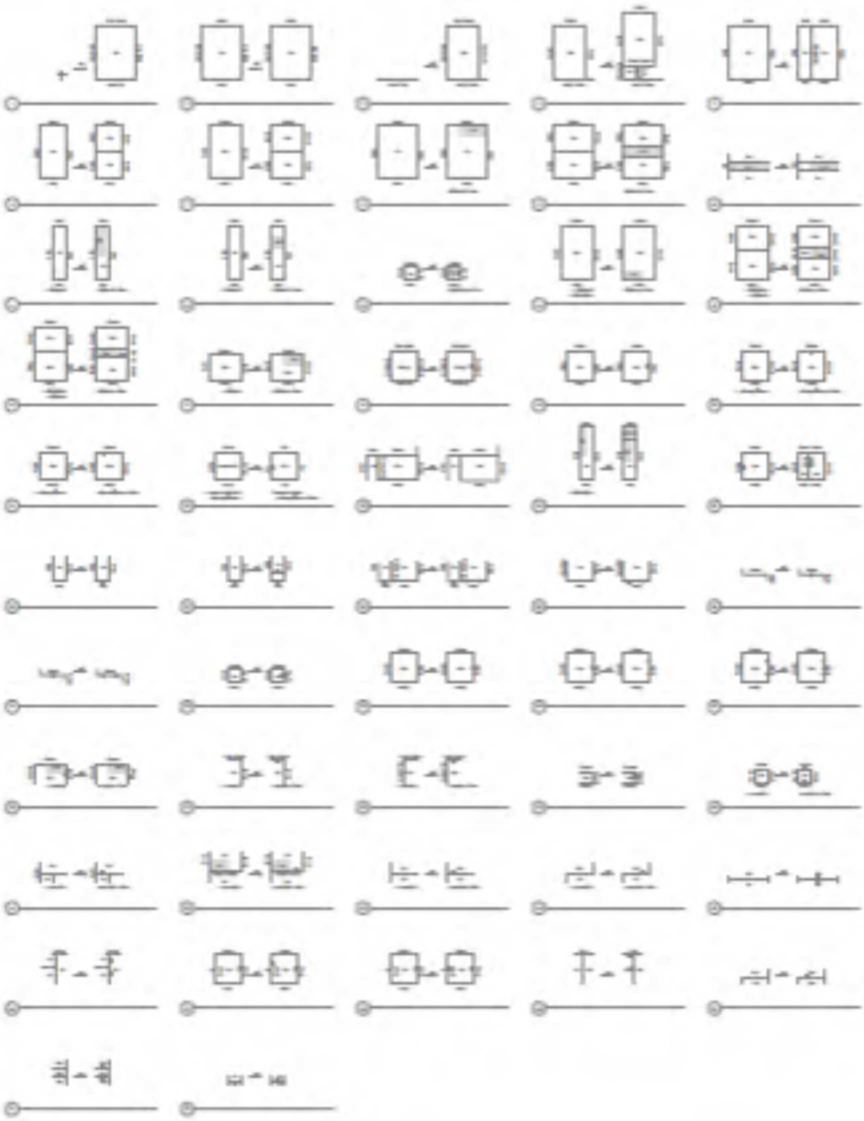
Possible layouts for a given test case



ground truth

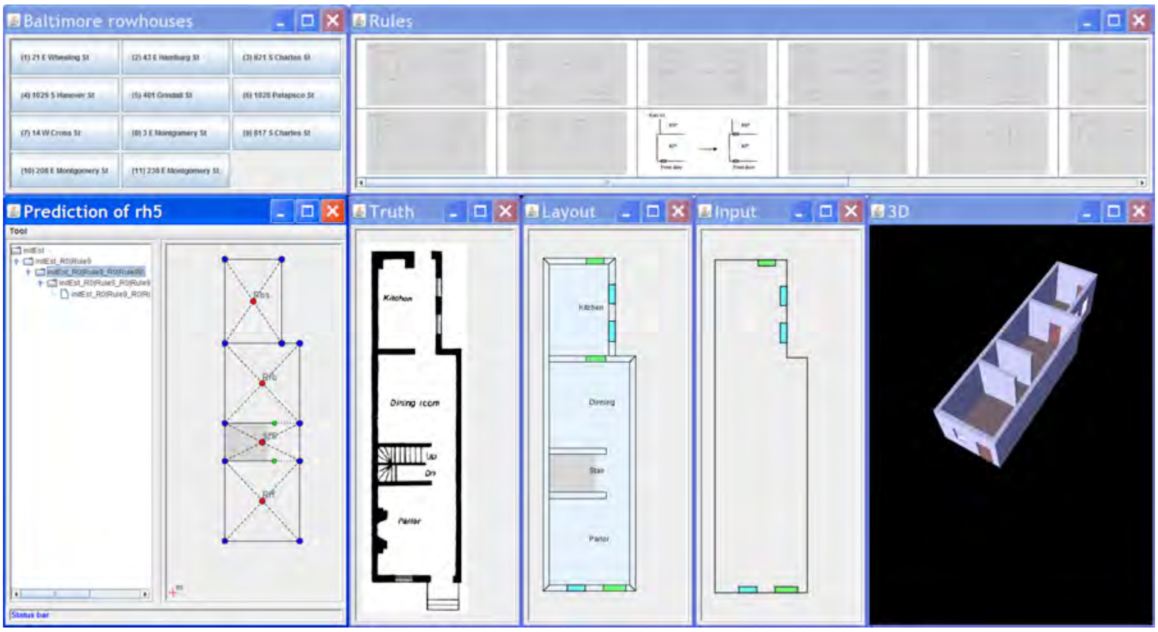
Test Case: The Baltimore Rowhouse

The Corpus



The Shape Rules

The Prototype



Students
Kui Yue and Casey Hickerson

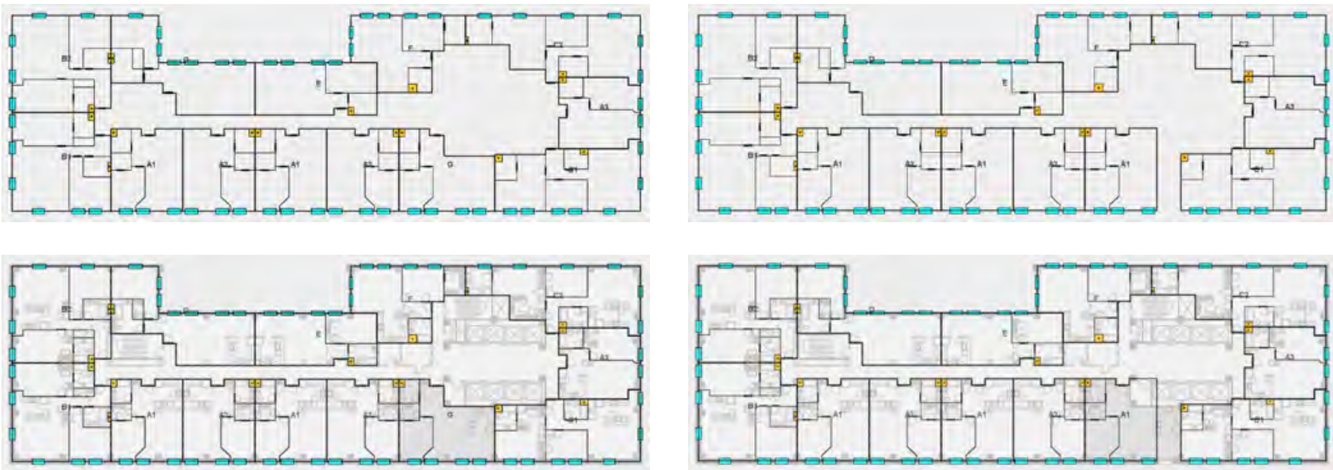
Collaborators
Francois Grobler, David McKay, Hyunjoo Kim, and Ajla Aksamjia

Publication

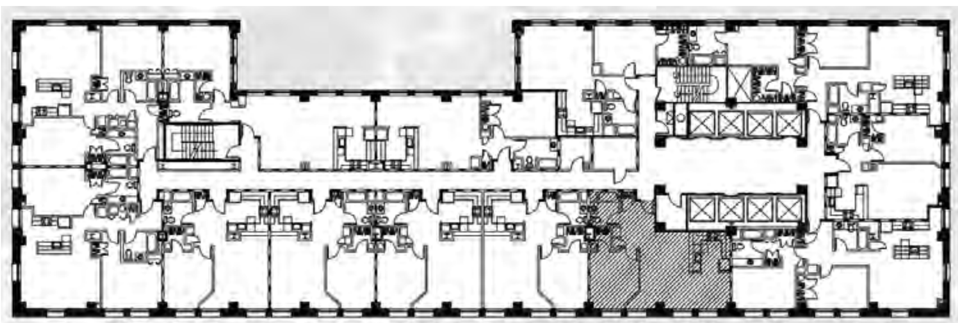
- Ajla Aksamija, Kui Yue, Hyoonjoo Kim, Francois Grobler and Ramesh Krishnamurti. Integration of knowledge-based and generative systems for building characterization and prediction. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 24, 3–16, 2010
- Kui Yue, Ramesh Krishnamurti and Francois Grobler. Computation-friendly shape grammars. *Joining languages and cultures and vision. CAAD futures 2009* (eds. T Tidafi and T Dorta), pp 757-770, Les Presses de l'Université de Montréal, Canada, June 2009
- Kui Yue and Ramesh Krishnamurti. Automatic extraction of building features from image data: how far are we? *Between man and machine – integration, intuition, intelligence, CAADRIA 2009* (eds. T-W Chang, E Champion, S-F Chien, and S-C Chiou), pp 727-736, Douliou, Taiwan: Shang Hao Print Co, April 2009
- Francois Grobler, Ajla Aksamija, Hyoonjoo Kim, Ramesh Krishnamurti, Kui Yue and Casey Hickerson. Ontologies and shape grammars: Communication between Knowledge-Based and Generative Systems. *Design Computing and Cognition: Proceedings of the Third International Conference on Design Computing and Cognition* (eds. JS Gero and AK Goel), pp 23-40, Springer, 2008
- Kui Yue and Ramesh Krishnamurti. A technique for implementing a computation-friendly shape grammar interpreter. *Design Computing and Cognition: Proceedings of the Third International Conference on Design Computing and Cognition* (eds. JS Gero and AK Goel), pp 61-80, Springer, 2008
- Kui Yue, Casey Hickerson and Ramesh Krishnamurti. Determining the interior layout of buildings describable by shape grammars. *CAADRIA 2008* (eds. W Nakapan, E Mahaek, K Teeraparbwong, and P Nilkaew), pp 117-124, Chiang-Mai: Pimniyom Press, April 2008
- Kui Yue and Ramesh Krishnamurti. Extracting building geometry from range images of construction sites. *Digitization and Globalization: CAADRIA 07* (eds. Yu Gang, Zhou Qi and Dong Wei), pp 459-466, Nanjing, China, April 2007

Extension to High-rise apartments

Possible layouts generated



Ground truth



sbim: **s**ustainable **b**uilding **i**nformation **m**odeling **2007 –**

Funded by Autodesk Inc, 2007-10.

Graduate Students: Tajin Biswas, Tsung-hsien Wang and Peng-hui Wan

Goal

Green CAD - green/sustainable building incorporating **design**, construction and operational practice that significantly reduce or eliminate the building's negative impact on the **environment** and to its **occupants.** The transition from conventional to sustainable building depends on a number of factors: **technological**, **environmental**, **economic** and **social**. From the perspective of computer-aided design, the first two are perhaps the most significant. To produce a design that fulfills a standard of sustainability requires more than designer assumptions or intuition. Current computer-aided design tools fall short of assisting designers with regard to meeting objective assessments of sustainable design during phases of design. Sustainability standards are typically specified by a green rating system, for example: LEED, BREEAM, Green Star, Casbee, Green Globes, etc.

Objectives

- ❖ To develop a methodology and tools for evaluating the environmental consequences of design-decision making.
- ❖ To assist designers to producing designs that fulfill certain sustainability requirements
- ❖ To build a general framework that cohesively represents the different sustainable rating systems so as to facilitate interaction with building information models.

Challenges

______ *of going green*

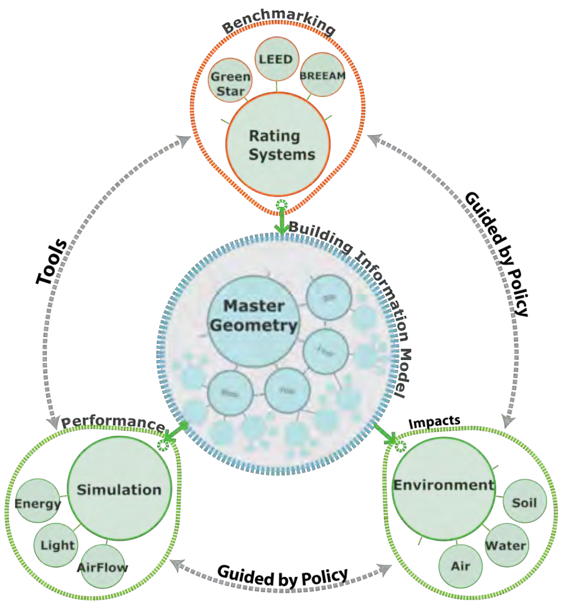
Evaluation	Open to interpretation
	Determining an adequate solution as per goal
Complexity of Evaluation	Multi-criteria and multi-level
	Iterative
Design goal representation	Function → Geometry
Multiple goals and constraints	Budget, Aesthetics, Environmental impact, Energy efficiency
Expert knowledge	Domain knowledge from individuals
Evolutionary in nature	New codes, benchmarks, emerging technologies

______ *of sustainable design*

Sustainable building design generally require validation by a rating system through the use of design tools and evaluations – although individually accessible, these are not available to designers in any usefully integrated way

There are no readily available schemata to represent the informational and computational needs of sustainable design rating systems

Sustainable building rating systems evolve; so too do their informational and computational needs

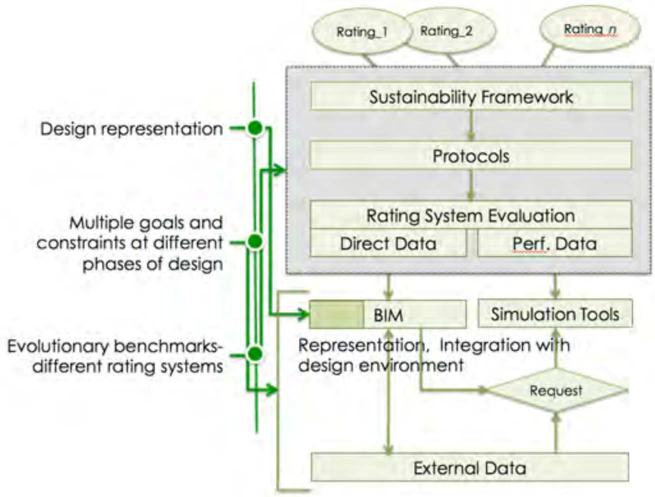


Strategy

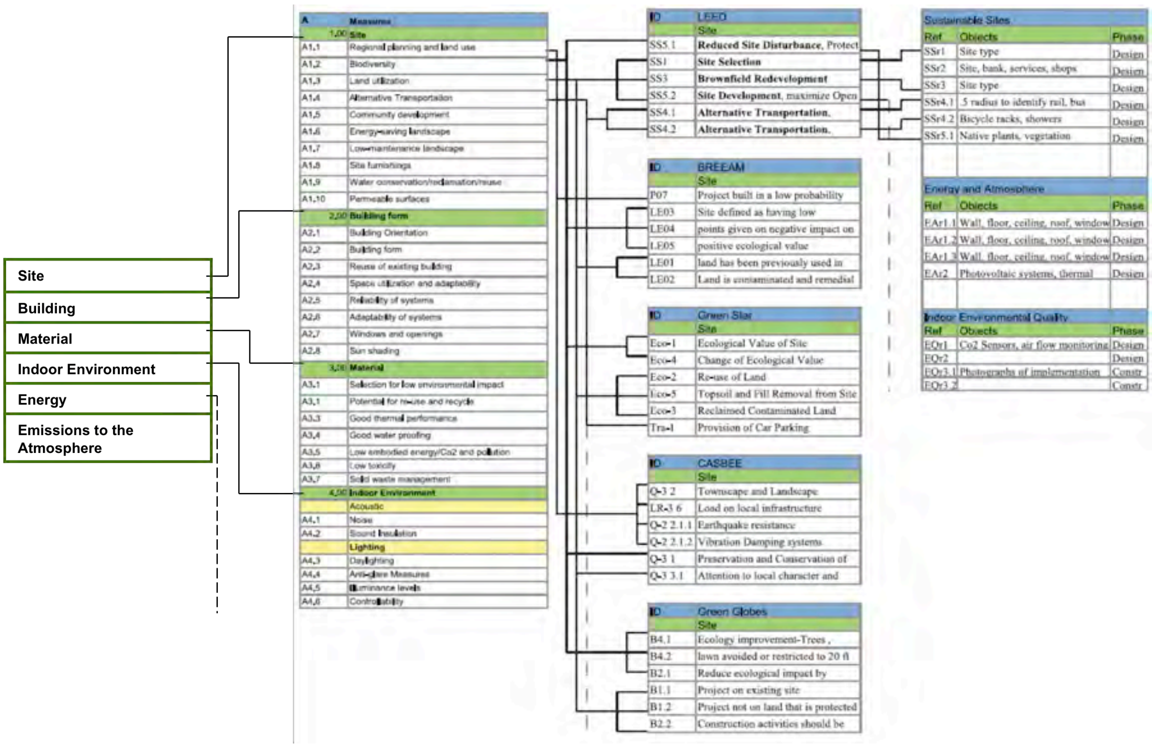
- ➢ Examine different sustainability rating systems through the lens of their inherent categories, criteria, scope and assessment methods
- ➢ Relate the different categories of sustainability measures from the rating systems to objects that are present in a building information model
- ➢ Build database support rules to query the building information model for relative information about a sustainability category
- ➢ Build databases, to access (or be queried) for default/relevant values prior to evaluation
- ➢ Offer designer feedback on the sustainability status of a project

Mapping Information

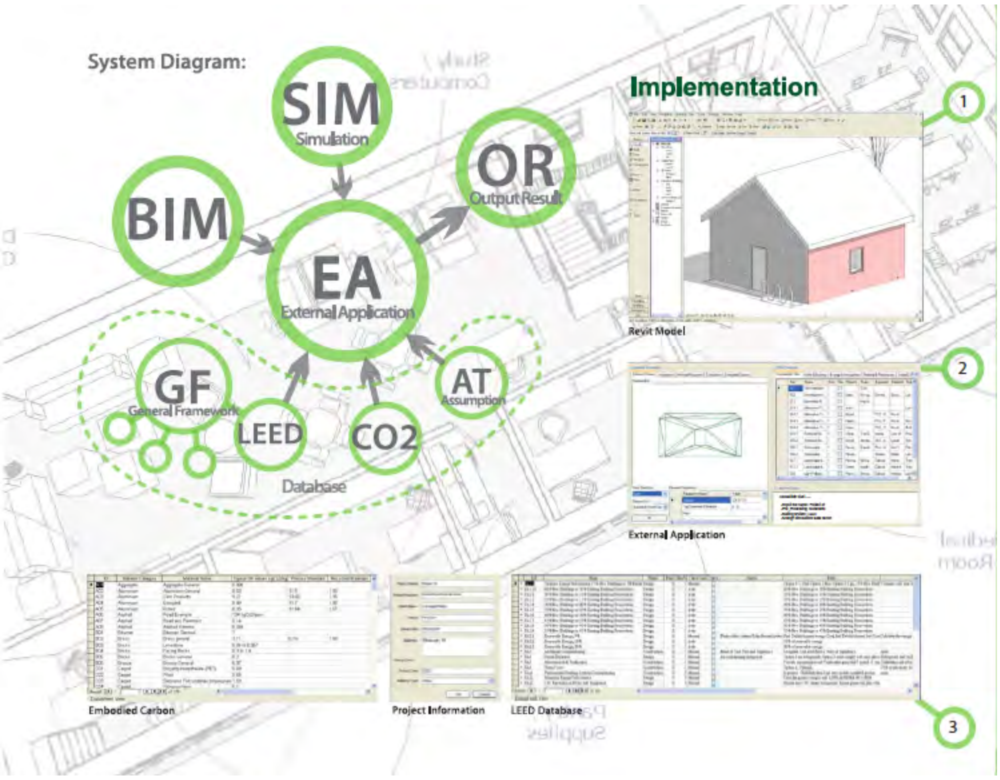
Sustainability category → Evaluation measures → Rating system requirements → Objects in the BIM



Sustainability Information Framework



An early implementation of the prototype

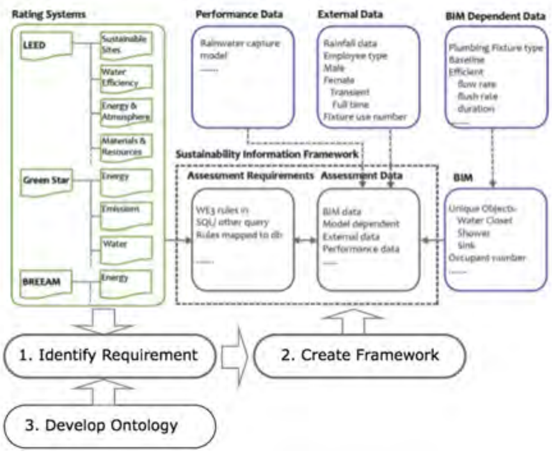


Gap Analysis

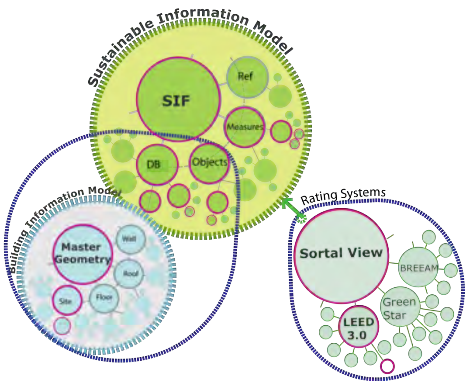
A gap analysis reveals the shortcomings of the building information model in meeting the needs of a green rating system's requirements.

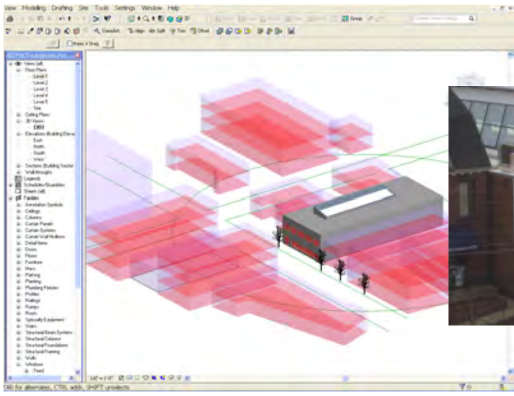
Gaps arise as a result of parameters or attributes missing in existing objects, missing objects, incomplete databases etc

The Present and Future

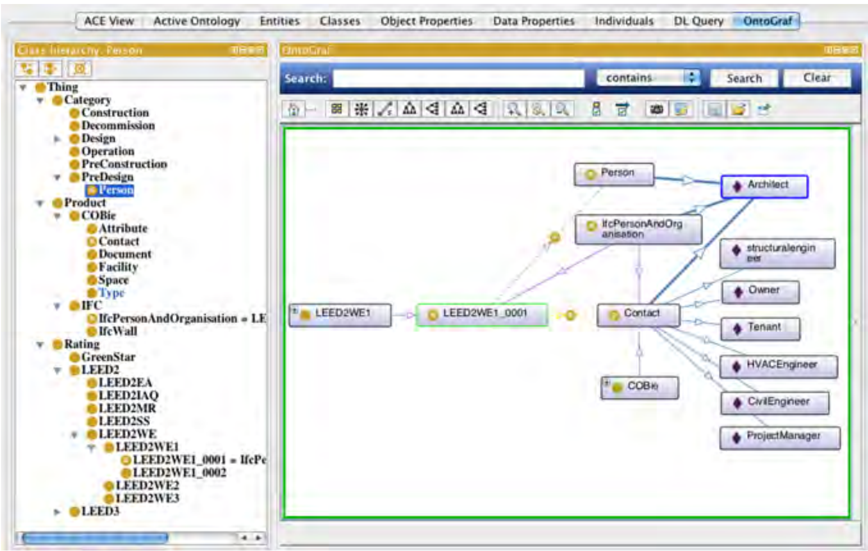


Intelligently convert environmental assessment requirements into knowledge that can be bridged with a BIM





Evolving standards *Implementations* *Green Designs*



Developing ontologies

Publications

- Tajin Biswas, Tsung-Hsien Wang, Ramesh Krishnamurti (2013) From Design To Pre-Certification Using Building Information Modeling, *Journal of Green Building*: Winter 2013,Volume 8, No. 1, pp 151-176. DOI: http://dx.doi.org/10.3992/jgb.8.1.151
- Ramesh Krishnamurti, Tajin Biswas, Tsung-Hsien Wang (2012) Modeling water use for sustainable urban design, *Digital Urban Modeling and Simulation* (eds. Stefan Müller Arisona, Gideon Aschwanden, Jan Halatsch, Peter Wonka) pp 138-155, CCIS 242, Springer-Verlag, Berlin Heidelberg [ISBN: 978-3-642-29757-1]
- Tajin Biswas, Tsung-Hsien Wang, Ramesh Krishnamurti (2009) Framework for sustainable building design, *Between Man and Machine – Integration, Intuition, Intelligence: CAADRIA 2009* (eds T-W Chang, E Champion, S-F Chien, S-C Chiou) pp 43-52,Taiwan: Shang Hao Print Co. Proceedings of the 14th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA), Yunlin, 22-25 April 2009
- Tajin Biswas, Tsung-Hsien Wang, Ramesh Krishnamurti (2009) Framework for supporting sustainable design, *Innovations for Building and Construction* (eds E Dado, R Behesti, K Zreik) pp 373-386, Europia Productions [ISBN: 978-2-909285-56-1] Proceedings of the 12th International Conference on Design Sciences and Technology (EuropIA12), Paris, 18-20 March 2009
- Tajin Biswas, Tsung-Hsien Wang, Ramesh Krishnamurti (2008) Integrating sustainable rating systems with building information models, *CAADRIA 2008* (eds W Nakapan, E Mahaek, K Teeraparbwong, P Nilkaew) pp 193-200, Chiang-Mai: Pimniyom Press. Proceedings of the 13th International Conference on Computer Aided Architectural Design Research in Asia, Chiang-Mai, 9-12 April 2008

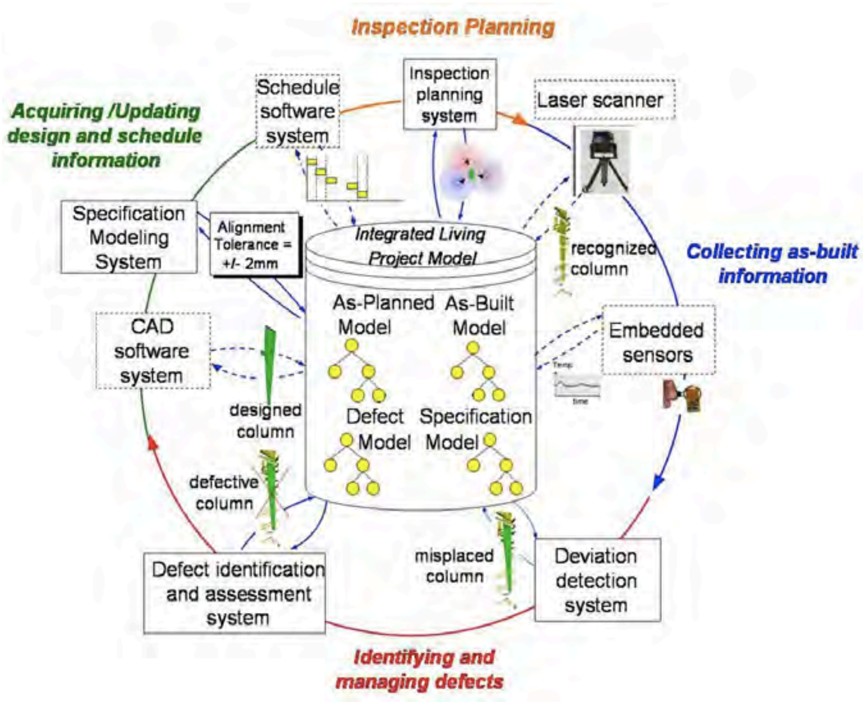
asdm*Con*: advanced sensor-based defect management at *Con*struction sites 2001– 06

Burcu Akinci, Martial Hebert, Ramesh Krishnamurti, Scott Thayer, Mark Patton, James Garrett & Daniel Huber

The Project

The **asdm*Con*** project was a collaboration of three disciplines — *Architecture, Robotics,* and *Civil and Environmental Engineering* — to investigate ways of integrating suites of emerging evaluation technologies to find, record, manage, and limit the impact of construction defects.

Frequent accurate assessment of the status of work-in-place, identifying critical spatio-temporal and quality related deviations, and predicting the impacts of these deviations during a construction project are necessary for active project control and for accurate project history.



Advances in generating 3D environments using laser scanning technologies, and collecting quality information about built environments using embedded and other advanced sensors, makes feasible the collecting quality as-built data.

The then current trends in the A/E/C industry for the use of integrated project models showed that a semantically rich integrated project database could support various project management and facility management functions.

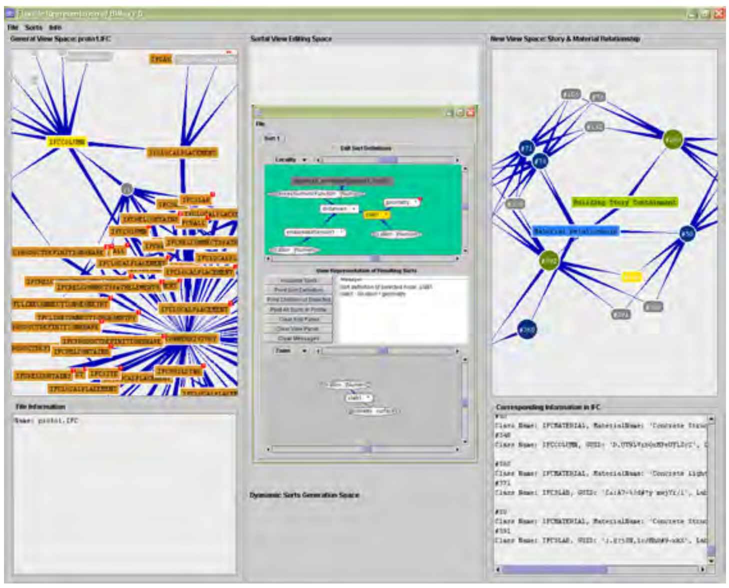
This research project combined, extended or built upon these advances to develop an automated early defect detection system

Flexible representation for design and construction

Construction projects commonly engage participants from various domains.

Integrating different views into a single project model, and supporting information exchange between alternative representations was a focus of our research.

We developed a representation structure that included a model of the as-built information, and provided a flexible decomposition of the product model.

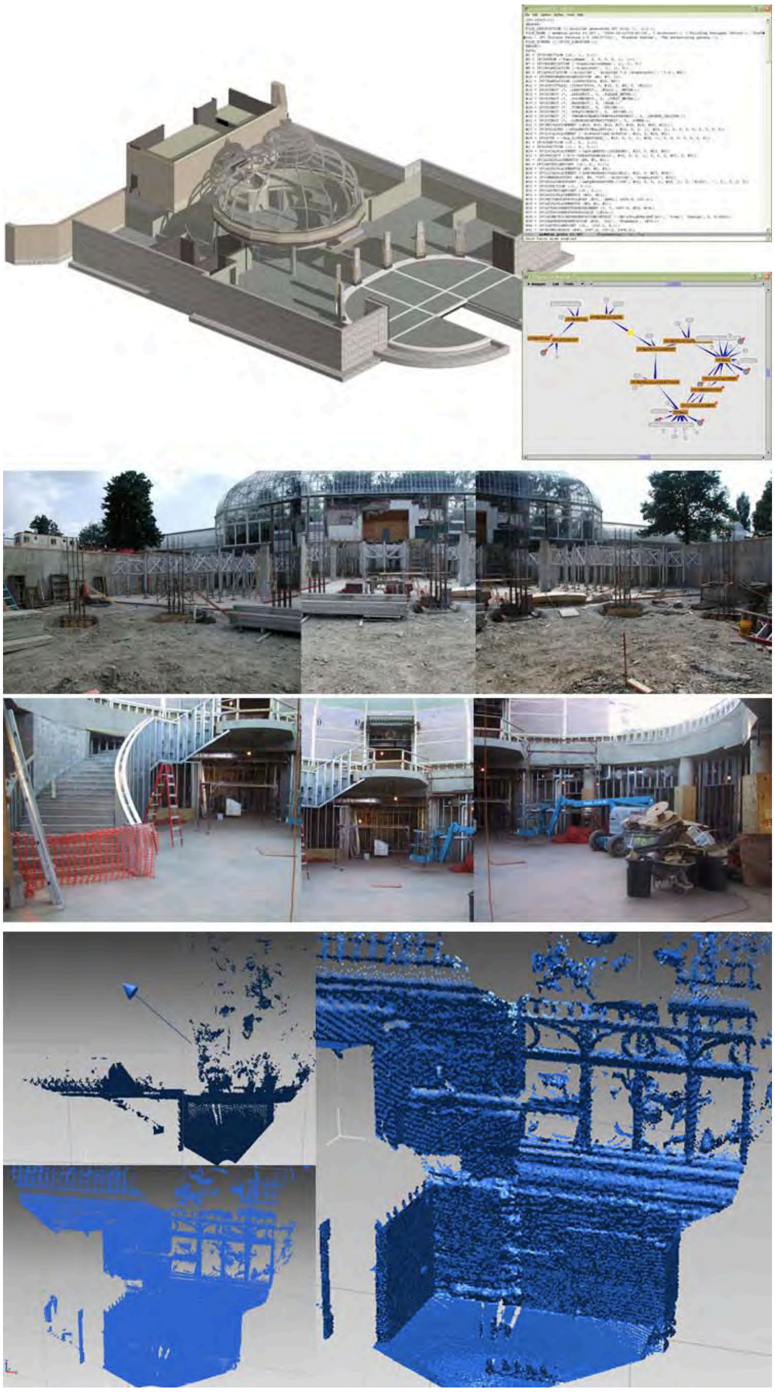


We implemented a system to provide:

i) A *general view* of the project model;
ii) A *predefined view* generated from a predefined representational schema for a defined user; and
iii) A *user-defined view* for an unspecified user.

A general view subsumes a predefined view and ***flexibility*** *is bootstrapped by the added capability of a user view.*

This work, based in *sorts*, offers a description through representational structures from formal compositions over primitive data types. *Sorts* allows for dynamic information entities, enabling creative design by supporting reinterpretations of existing design descriptions through emergence. This work was developed with Rudi Stouffs and his researchers at TU Delft.



Through case studies, we were able to capture dynamic changes in construction, including update, addition, and removal of data from the project model, and present an effective representation for the specific needs of the various experts.

The idea of individual needs, a complex project model and its representation emphasized the important of user interaction.

Our research into flexible representation focused on database form, queries, and user interaction, and included how to integrate and maximize the use of collected data sets from embedded sensors and laser scanning.

The case studies—from design to erection—included:

(i) A steel structure warehouse;
(ii) A pre-cast concrete factory;
(iii) A cast-in-place concrete multiuse office building; and
(iv) A steel and glass structured dome renovation with a cast-in-place concrete entrance hall.

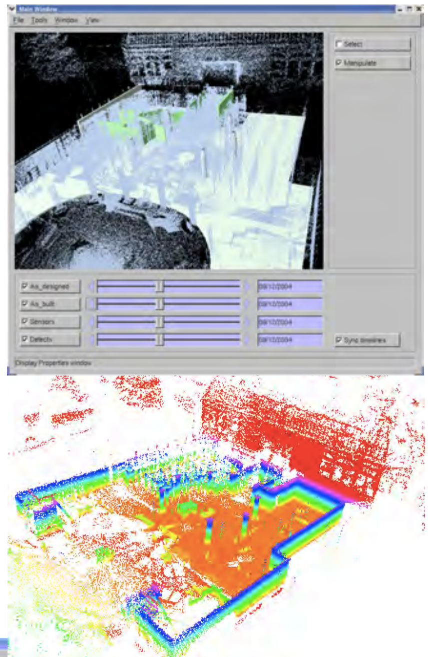
Case study example; as-designed model, site condition, and as-built model

Object recognition and visualization ______________________

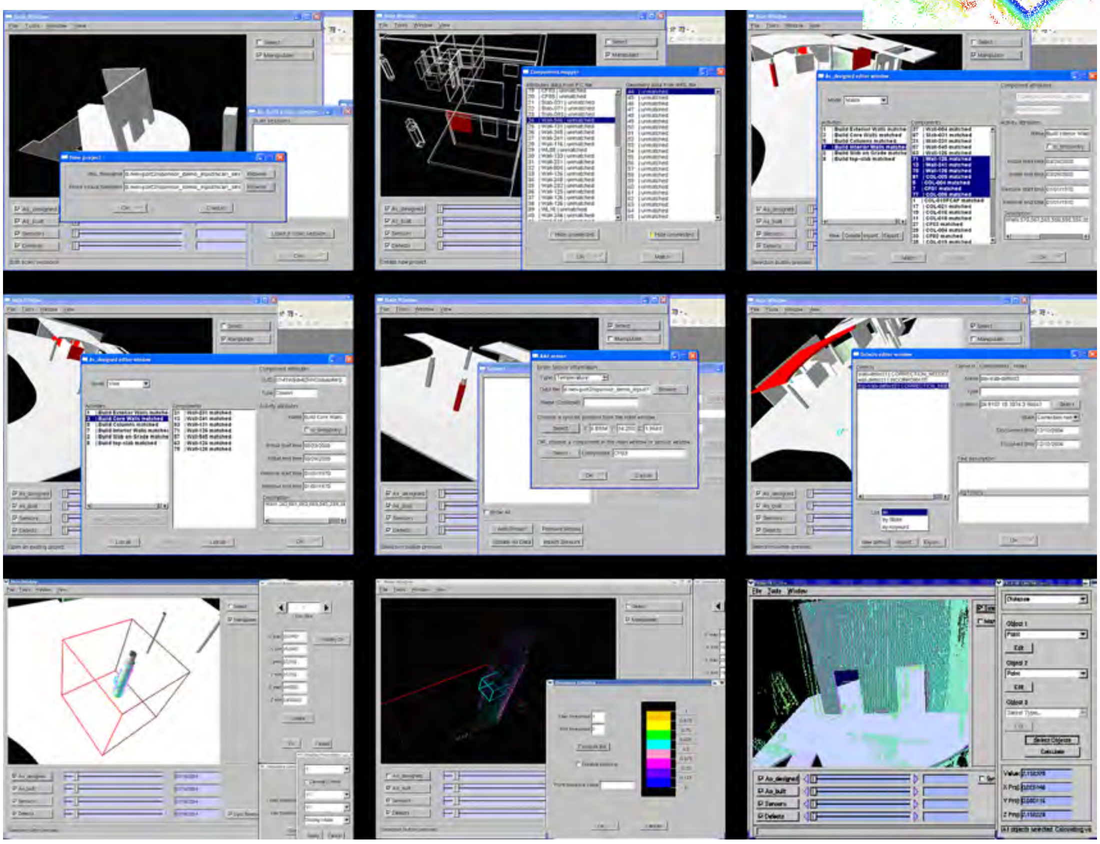
We applied object recognition techniques to defect detection.

Using 3D modeling and recognition techniques, construction defects are detected whilst a building is in construction. A time-varying 3D reconstruction of the as-built condition of the construction site is compared to a 3D model derived from the design plan; defects are presented through a visual user interface.

The visualization environment allows user interaction and analysis of the integrated project model. It incorporates functionalities for viewing major components of the project model (as-built model, as-designed-model, etc.), manual analysis of potential defects (e.g., deviation measurement), and defect management. The visualization environment provides a central interface for accessing and controlling different tasks in the processing cycle.

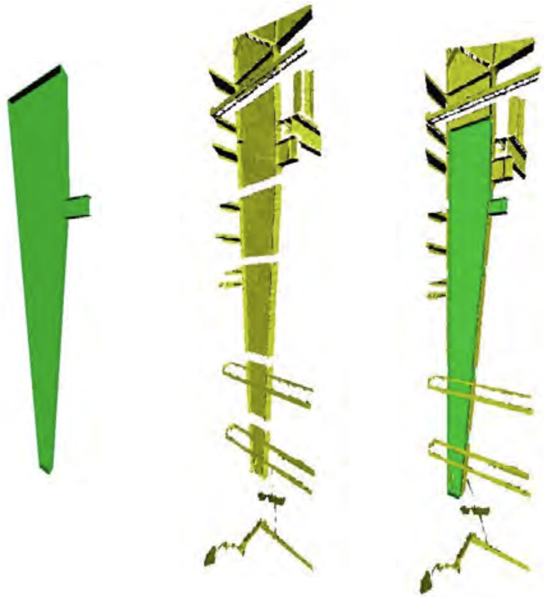


Construction defect visualization environment



Students: Two doctoral students, Kuhn Park and Kui Yue were supported on this project. In addition, four undergraduate architecture students John Oduroe, Kunal Patel, Tomonori Tsujita, and Donald Harvey had research opportunities to work on this project.

Project website: http://www.ce.cmu.edu/~ITR



An early example of as-designed based object recognition

Publications ___________________________________

Rudi Stouffs, Ramesh Krishnamurti, Kuhn Park. Sortal Structures: Supporting Representational Flexibility for Building Domain Processes. *Computer-aided Civil and Infrastructure Engineering*, **22**(2), 98-116, 2007. Special Issue on Product Models (Eds. A Watson and C M Eastman) DOI: http://dx.doi.org/10.1111/j.1467-8667.2006.00473.x

Kui Yue and Ramesh Krishnamurti. Extracting building geometry from range images of construction sites. *Digitization and Globalization: CAADRIA 07* (eds. Yu Gang, Zhou Qi and Dong Wei), pp 459-466, Nanjing, China, April 2007

Rudi Stouffs, Ramesh Krishnamurti, Albert ter Haar. A sortal building model supporting interdisciplinary design communication. *Building on IT: Joint International Conference on Computing and Decision Making in Civil and Building Engineering* (Eds. H Rivard, E Miresco and H Melhem) pp 2056-2065, Montréal, Canada, 2006

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Kuhn Park, Viraj Srivastava, Ramesh Krishnamurti. SmartBIM: The progression of integrated building information model over the lifecycle of a building. *ACADIA 2005: Smart Architecture - Integration of Digital and Building Technologies*, Savannah, Georgia, October 2005

Kuhn Park, Ramesh Krishnamurti. Diary of a building. Poster Paper, *CAADfutures2005,* Vienna, June 2005

Kuhn Park, Ramesh Krishnamurti. Digital diary of a building. *CAADRIA'05* (Ed. A Bhatt), vol 2, pp 15-25, TVB School of Habitat Studies, New Delhi, India, April 2005

Rudi Stouffs, Ramesh Krishnamurti. Data views, data recognition, design queries and design rules. *Design Computing and Cognition'04* (Ed. JS Gero), pp 219-238, Kluwer Academic Publishers, Dordrecht, 2004

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Kuhn Park, Ramesh Krishnamurti. Flexible design representation for construction. *CAADRIA'04* (Eds. Hyun Soo Lee and Jin Won Choi), pp 671-680, Yonsei University Press, Seoul, Korea, 2004

Chris Gordon, Frank Boukamp, Daniel Huber, Ed Latimer, Kuhn Park, Burcu Akinci. Combining Reality Capture Technologies for Construction Defect Detection: A Case Study. *EIA9: E-Activities and Intelligent Support in Design and the Built Environment, 9th EuropIA International Conference*, pp 99-108, Istanbul, Turkey, 2003

The **asdm*Con*** project was funded by a five-year grant (NSF-CMS-0121549) from the National Science Foundation under the Information Technology Research initiative.

SORTS: a concept for representational flexibility (1) **1996 – 2008***

* With Rudi Stouffs (2), Delft University of Technology, where research on *Sorts* is still on-going

(1) Work on *Sorts* was funded in part by the National Science Foundation (NSF-CMS-0121549)
(2) Rudi Stouffs was funded by Netherlands Organization for Scientific Research (NWO)

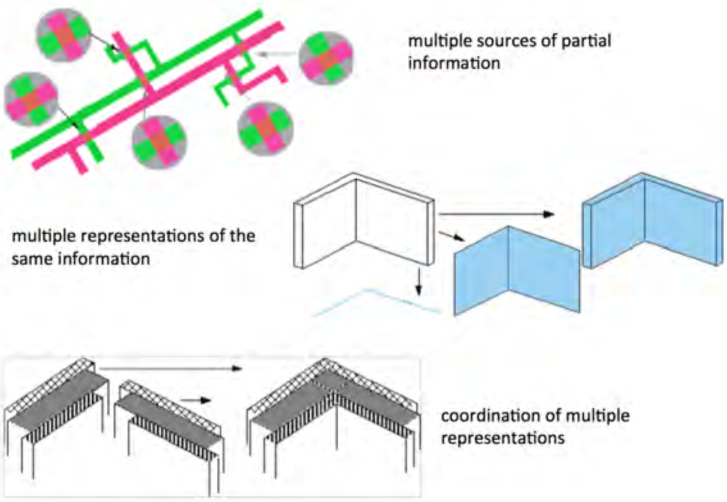
Two distinct notions inspired the idea for *Sorts*: the first, a talk by Chuck Eastman on information coverage between distinct representational schemes in the same domain, and the other, the need to deal with weighted shapes.

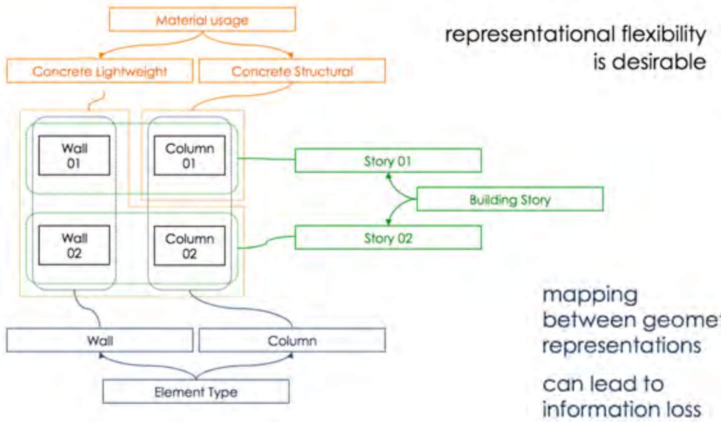
Sorts
- Provide a semi-constructive algebraic formalism for design representations that enables these to be compared with respect to scope and coverage.
- Present a uniform approach to dealing with and manipulating data constructs.
- Offer representations specified by formal compositional relationships over primitive data types.

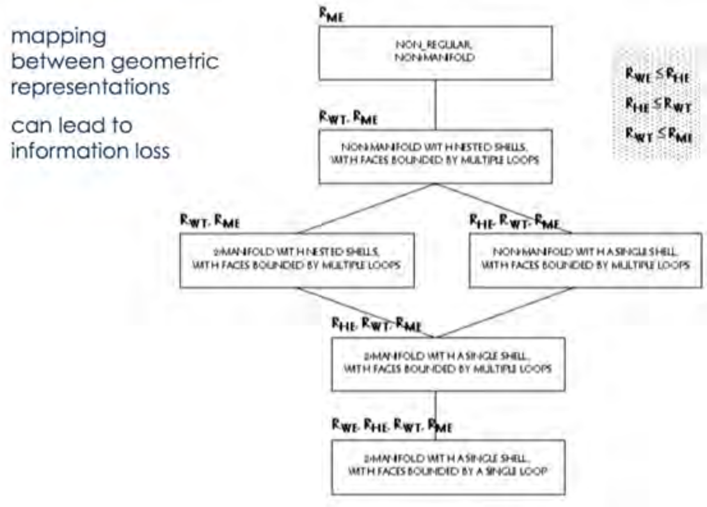
Formalism allows for dynamic information entities; enables creative design by supporting re-interpretations of existing design descriptions through emergent forms; and considers a methodology for dealing with such dynamism within a design application; that is, it offers representational flexibility.

Sortal descriptions are data structure representations based on *sorts*.

Sortal issues in pictures







CAD documents and *Sorts*

Within the conceptual phase of design, architects and designers study relevant precedents and collect and look at design and other documents as sources of knowledge and inspiration. Generally, electronic design document libraries or image archives serve to collect this information, separately from the CAD or modeling environment that is used to shape the design. *Sorts* provides a formalism for constructing design representations that can assist in specifying and maintaining relationships between design-related documents and the elements within a CAD model. Specifying such relationships helps to organize the information contained within these documents in relation to the CAD model. Consider a representational structure that reflects on (part of) the CAD model, for example composed of element IDs and descriptions. A corresponding data construct can easily be generated, automatically, from the CAD data. This representational structure can then be extended to allow for document references to be associated with the CAD elements. Using a graphical interface, the user can specify both the references and their associations to CAD elements. When the CAD model is subsequently changed, the data reflecting on the CAD model can be regenerated, while the associated data can be retrieved from the original representational structure using an automatic conversion based on the matching of both representational structures. The *sorts* formalism supports such matching of representational structures, by means of a subsumption relationship over representational structures and a behavioral specification for data constructs. Merging both data constructs re-associates document references to CAD elements, on condition that the respective element IDs have not changed.

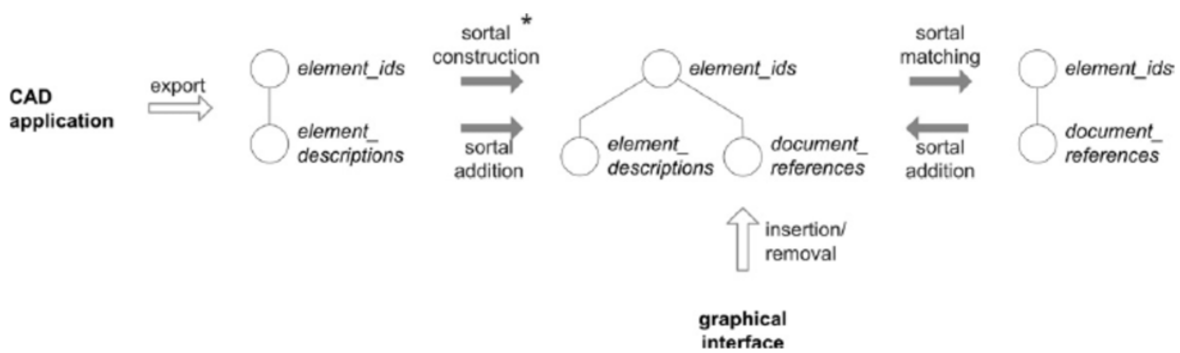
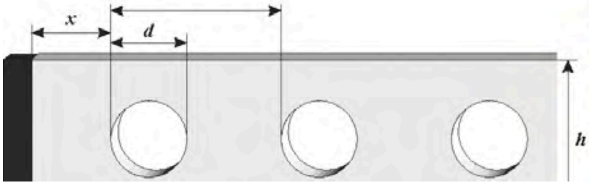
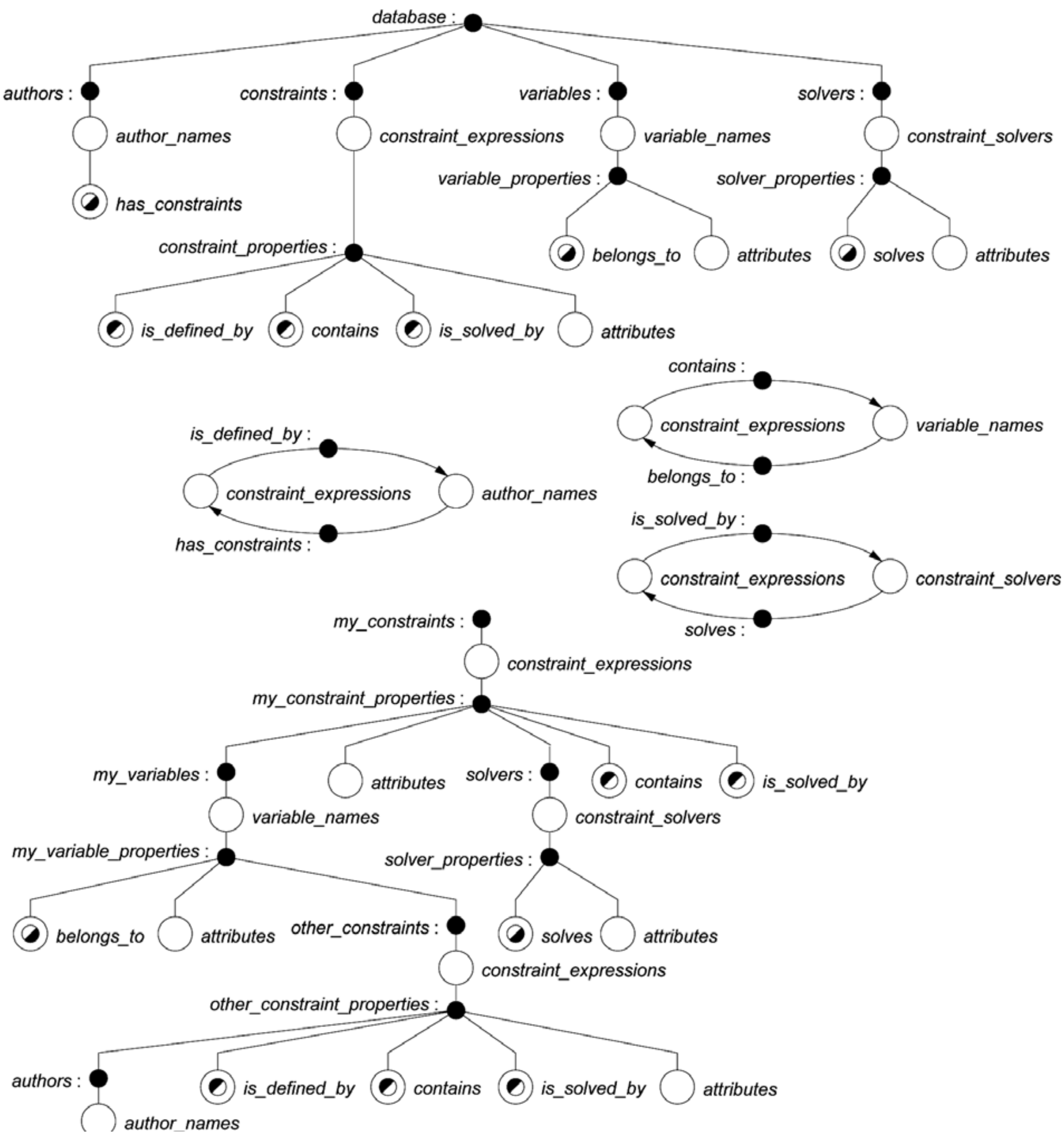


Figure. Schematic overview of the process, of relating design documents to CAD elements using *sorts*. Filled arrows denote automatic *sortal* conversions; * *sortal* constructions applied once initially

The first practical application of *sorts* was developed in the context of a project building a toolset for the virtual AEC industry, in particular, integrating a numerical constraint solver in a document-centric collaboration environment.

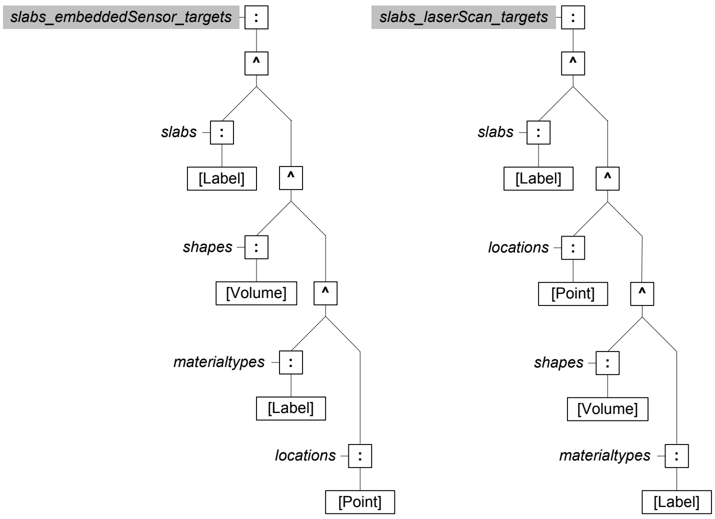




Sorts depicting a database view (above) and a user view (below) represent design information in the form of design constraints and related information. Property *sorts* (middle) represent the various links between the constraint expressions and, respectively, the author names, variable names, and constraint solvers.

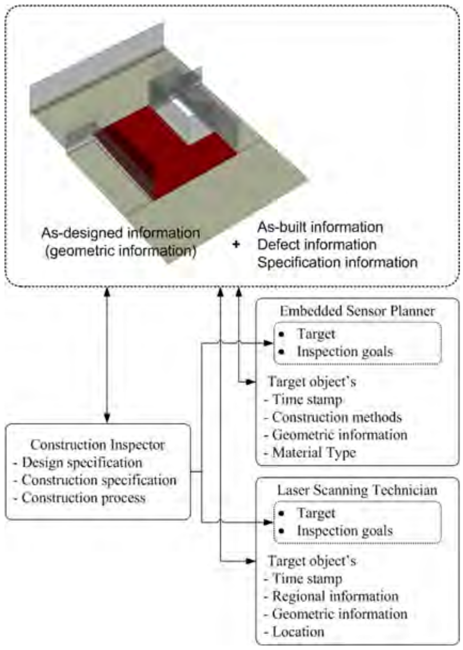
Sorts in the context of building construction, within a larger project that investigates ways of integrating suites of emerging evaluation technologies to help find, record, manage, and limit the impact of construction defects.

sort slabs : [Label];
sort *materialtypes* : [Label];
sort *locations* : [Point]
sort *shapes* : [Volume];
sort *slabs_embeddedSensor_targets* : *slabs* ^ *shapes* ^ *materialtypes* ^ *locations*;
sort *slabs_laserScan_targets* : *slabs* ^ *locations* ^ *shapes* ^ *materialtypes*;

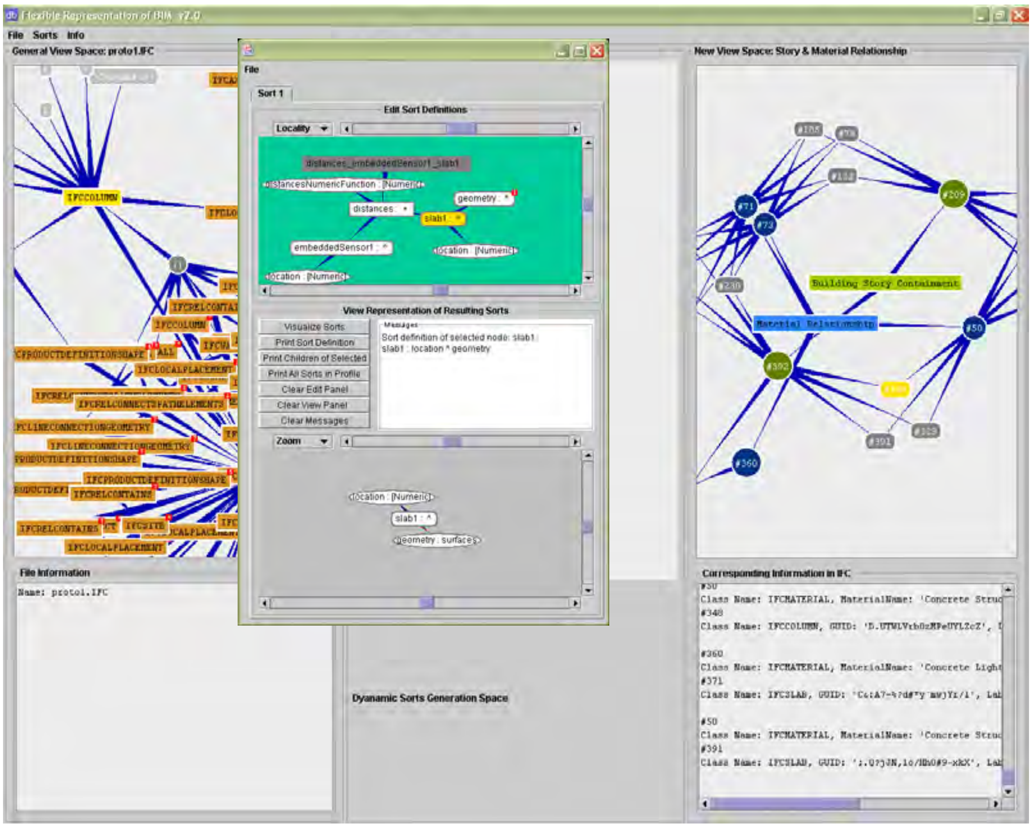


form $slabs = *slabs_embeddedSensor_targets*:
{ "slab1"
{ < ... >
{ "target1"
{ 1/5(61,42,8),
1/5(61,47,6) } } } };

form $slabs = *slabs_laserScan_targets*:
{ "slab1"
{ 1/5(61,42,8)
{ < ... >
{ "target1" } },
1/5(61,47,6)
{ < ... >
{ "target1" } } } };

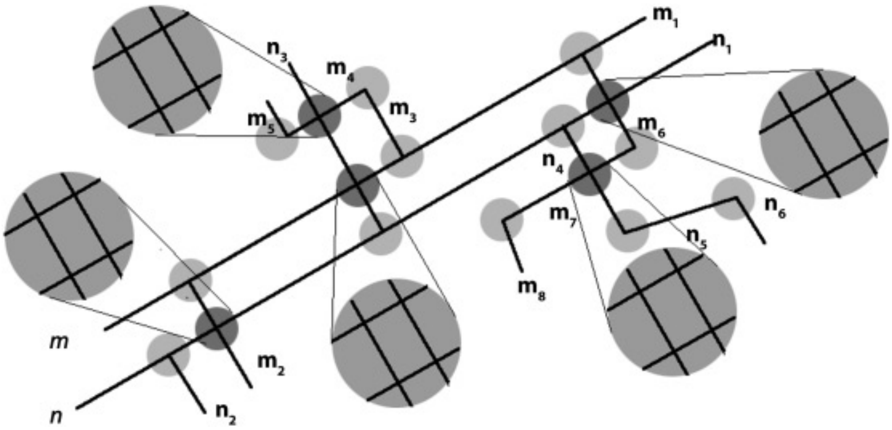


Different representational needs on a slab



Using *Sorts* to solve problems

The diagram below shows networks for utilities, *m* and *n*. Each straight-line length of pipe is identified by its network utility name, and numbered 1, 2, 3, . . . Gray circles indicate pipe intersections; of these, the darker circles signify possible interference.
An easy way to solve the design problem is to define exogenously, a "view" of labeled points of intersection as follows: each such point is associated with labels identifying the pipes' network whenever the pipes do intersect. In this view, these "sorted" intersection points are labeled by one or both networks i.e., labeled in the special way!. Clearly, checking for pipe interference reduces to counting doubly labeled points of intersection in this created view. This information is used in the search, but is not needed again once a



Publications

On sorts

- Rudi Stouffs (2008) Constructing design representations using a sortal approach, *Advanced Engineering Informatics* 22(1), 71-89. DOI: http://dx.doi.org/10.1016/j.aei.2007.08.007
- Rudi Stouffs, Ramesh Krishnamurti, Kuhn Park (2007) Sortal Structures: Supporting Representational Flexibility for Building Domain Processes, *Computer-Aided Civil and Infrastructure Engineering* Volume 22, Issue 2, 98–116, February 2007. DOI: http://dx.doi.org/10.1111/j.1467-8667.2006.00473.x
- Rudi Stouffs, Albert ter Haar (2006) Constructing design representations, *Intelligent Computing in Engineering and Architecture* (ed. I.F.C. Smith), *Lecture Notes in Artificial Intelligence*, vol. 4200, pp. 653-662, Springer, Berlin, 2006
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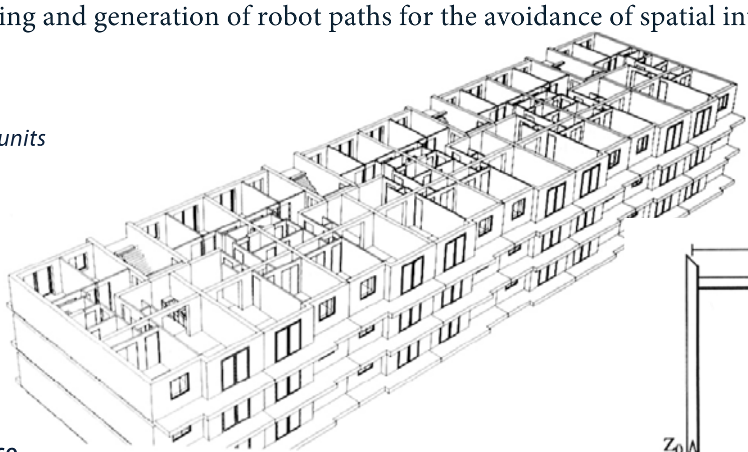
rubicon: rule based simulation applied to robotized building construction **1991 – 92**

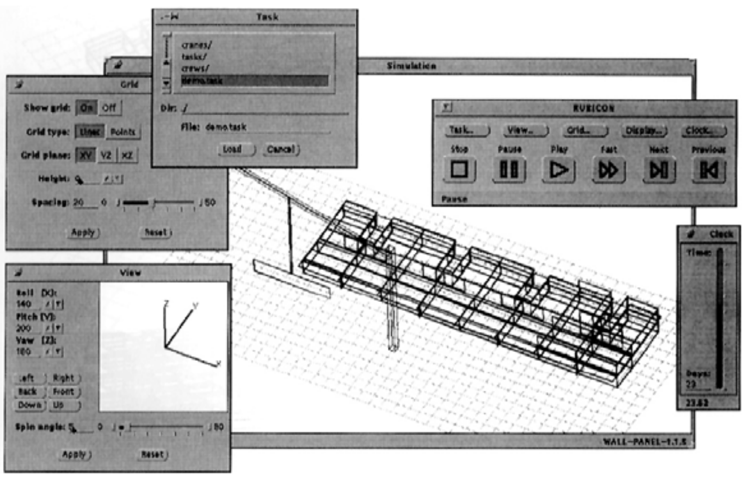
In collaboration with Irving Oppenheim, Stephen Lee, and Rudi Stouffs
The work was funded by the **Japan Research Institute.**

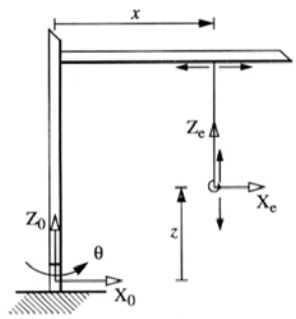
The **objective** was to evaluate the feasibility and productivity of robot agents in construction. We specified a general representation for robots in building construction that uniformly characterizes a wide variety of automated agents, using motion rules as a means of establishing the configuration of an agent at any given time. We developed a motion language to describe the behavior of automated agents in a dynamically changing environment and in cooperation with human labor crews. We implemented a rule based simulation program for robot assisted assembly of panelized constructions with particular reference to rule–based checking and generation of robot paths for the avoidance of spatial interference.

Typical precast concrete housing units for robotized construction

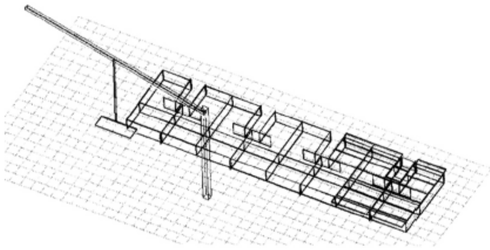


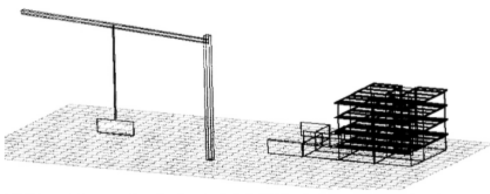
The RUBICON graphical interface





A robot crane





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basic research into **Shape Grammars** 1980—

In collaboration with George Stiny, Lionel March, Chris Earl, Christian Giraud and Francois Grobler and former students: Rudi Stouffs, Shang-chia Chiou, Kui Yue and Casey Hickerson

*A **shape grammar** is a system of rewriting shape rules.*

A design is generated as a sequence of shapes; each shape in the sequence produces the next shape in the sequence by substituting a part of the shape for another part. The two parts constitute a shape rule. Shapes can be tagged with markers, to deal with functional and other non-spatial features. Markers can be erased and added during design generation. Markers can be specified in the shape rules. Shape rules are usually further classified into stages; in this way, layout generation can be broken down into phases. A shape grammar is developed from a methodological examination of corpora of designs specified by a set of characteristics.

Computer Implementation

. In 1981 I wrote the **first complete implementation** of a shape grammar interpreter (SGI) that could handle emergent shapes, based on a complete and uniform representation of two-dimensional shapes as finite sets of straight lines based on a theory of rational shapes that I hade developed for the implementation. Since then, for nearly 32 years, periodically, with colleagues and students I have revisited the subject.

My early work looked at shape arithmetic and recognition for line and plane shapes in two- and three dimensions. With Rudi Stouffs, we developed the theory and algorithms for shape arithmetic and recognition for shapes in three dimensions and; developed an algebraic theory of shapes and implemented a toolkit for shape manipulation in C and in Java.

A shape grammar interpreter can be expressed by the following equation: $new = current - \mathrm{t}(left) + \mathrm{t}(right)$ where $\mathrm{t}(left) \leq current$, which reads as follows: a *new* shape is constructed from the *current* shape by removing a *transformation*, t, of a shape, *left*, by the same transformation of the shape, *right*, whenever the *left* shape occurs in the *current* shape under the said transformation, t. The relationship $left \rightarrow right$ specifies a shape rule and the equation above describes a *rule application*. The equation expresses five different issues associated with rule application.

Shape representation	Initially developed a two-part maximal element representation comprising boundaries and carriers, such that — *every shape is the sum of an unique finite set of disjoint segments with disjoint boundaries.* Moreover, the *boundary of a maximal shape is the sum (or symmetric difference) of the boundaries of its maximal segments.*
Shape arithmetic	Shapes are defined over an Boolean ring $U_{n,d}$, as n-dimensional shapes embedded in a d-dimensional universe. Algorithms were developed for algebras U_0 through U_3
Transformation	Representation of geometrical transformations
Shape recognition	Determination of subshapes that correspond to a transformation of the left side of a shape rule. Algorithms were developed for algebras U_0 through U_3 and cross-products.
Shape rule application and control	An interface issue that has not been fully resolved.

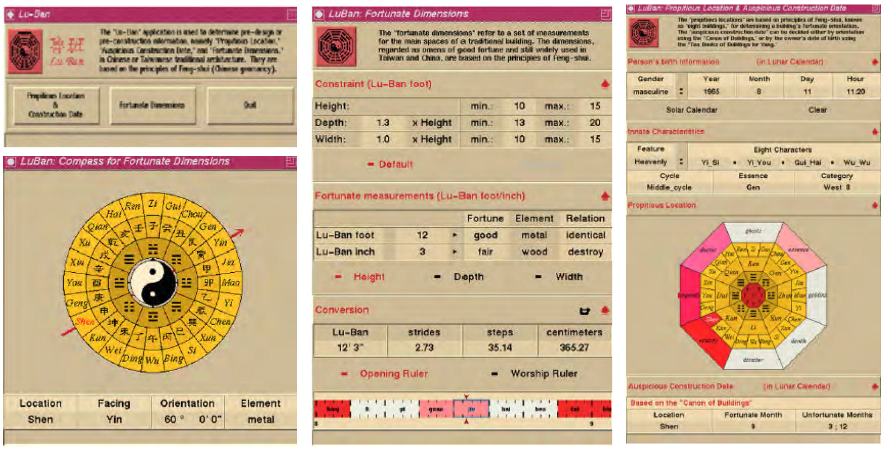
The table below summarizes the ***state-of-the-art***.

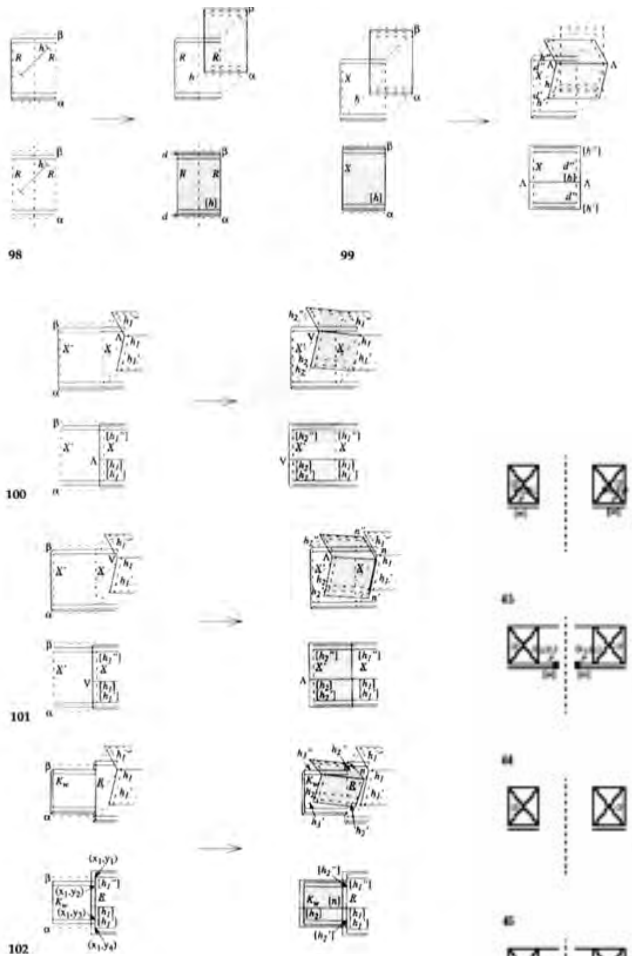
U_0	$U_{0,0}$	$U_{0,1}$	$U_{0,2}$	$U_{0,3}$
U_1		$U_{1,1}$	$U_{1,2}$	$U_{1,3}$
U_2			$U_{2,2}$	$U_{2,3}$
U_3				$U_{3,3}$

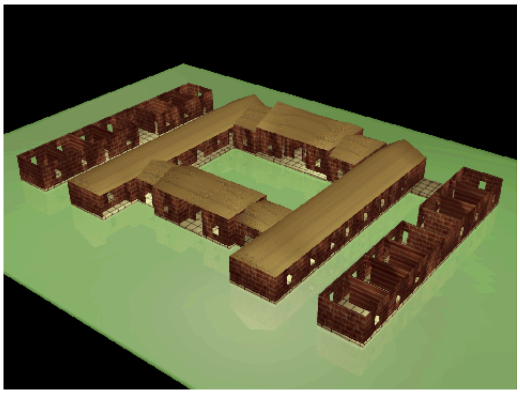
	Solved (fixed) shape problems
	Representation & Arithmetic
	+ Recognition for fixed shapes
	+ Grammar implementation

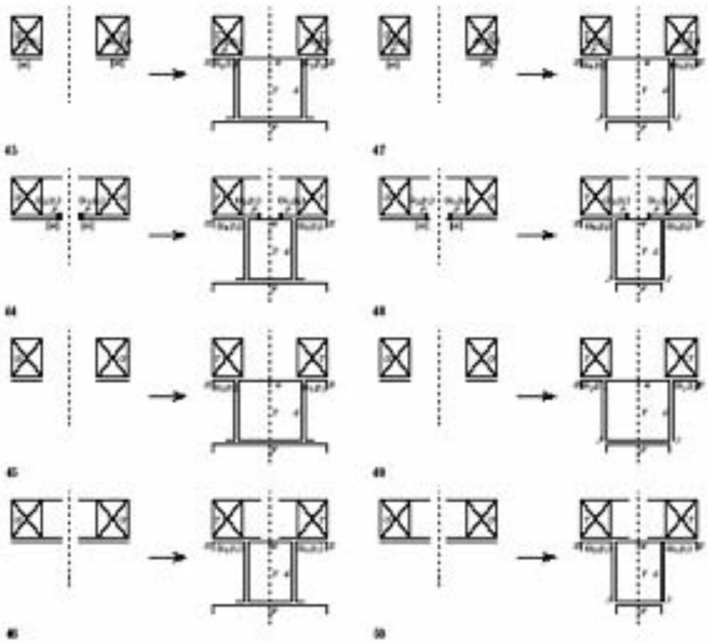
Chinese Vernacular Architecture

With my former doctoral student Shang-chia Chiou, I developed shape grammars for vernacular Taiwanese architecture, traditional *san-he-yuan* houses and temples. A feature of this grammar, quite distinct from conventional shape grammars, is that the grammar did not rely upon a corpus of forms from which shape rules were induced. Instead, the rules were derived purely from an analysis of traditional processes of design and construction based on precepts of *feng-shui* and geomancy. The rules were tested out on a number of extant complex vernacular houses.

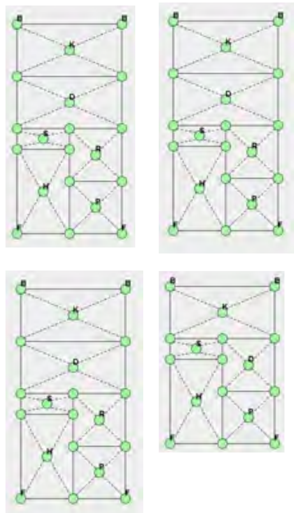


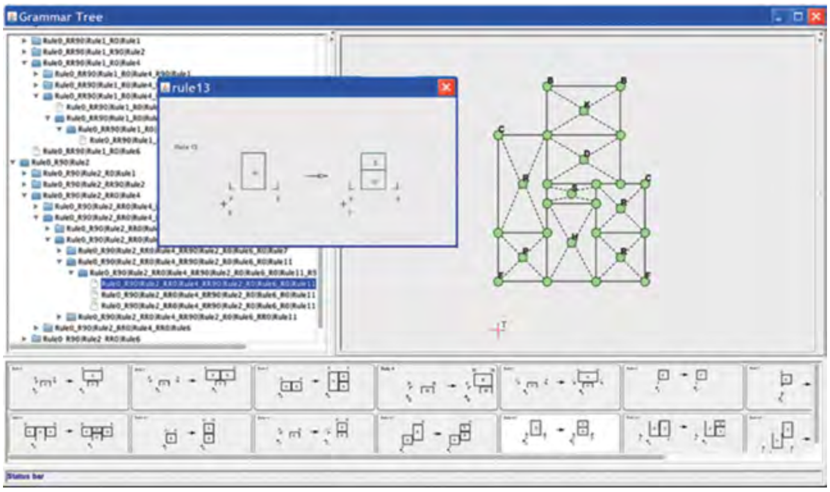




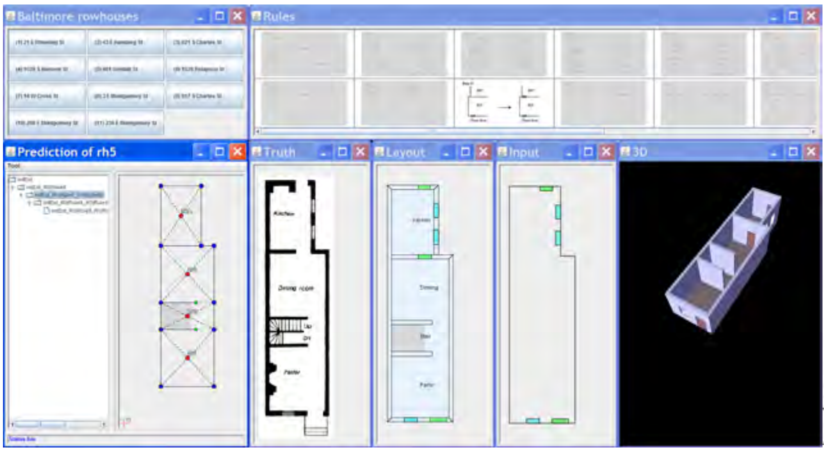


With Kui Yue, I have explored a class of parametric shape grammars, termed ***tractable shape grammars***, for which we have developed a paradigm for developing viable parametric shape grammar interpreters. Our investigations yielded important theoretical results for this class of shape grammars and their relationship to computability. Two interpreters were constructed and tested on new shape grammars for Queen Anne Houses and the Baltimore Rowhouse.

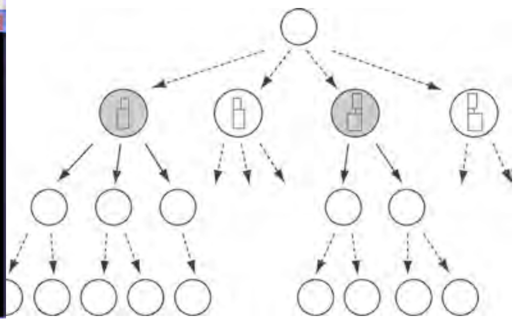


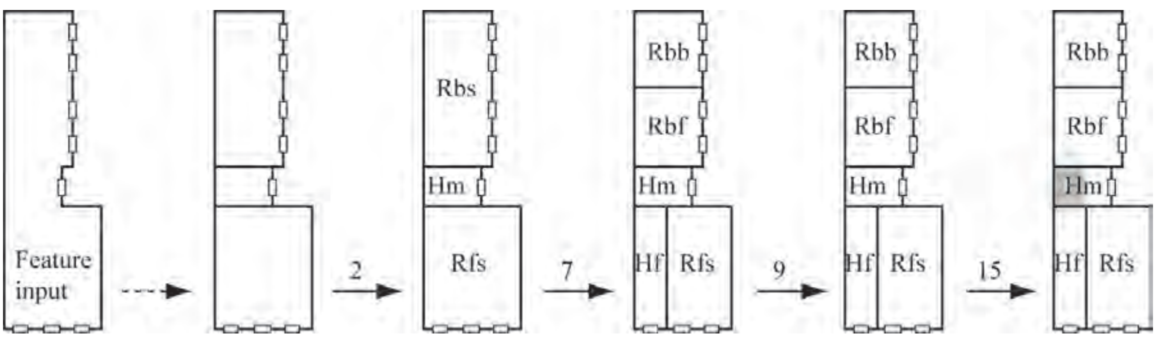


The **Queen Anne** shape grammar as a working prototype interpreter



The **Baltimore Rowhouse** shape grammar as a tree and as working prototype





One of the major results of our work on tractable shape shapes is a unification of shape grammar definition that have evolved over the past 40 years.

Evolution of shape grammar definitions

	Definition	Features
Marker-driven shape grammars	SG-DEF-1971	Based on shapes as both vocabulary and marker elements. Introduces the analogy to generative string grammars. Emergent shapes are implicit in 'surprises.'
	SG-DEF-1974	Based on closed polygons, curves. No treatment of emergent shapes. Theoretical basis of the first ever shape grammar interpreter implemented (Gips, 1974). Certain elements of the shape grammar were treated symbolically in Gips' implementation.
	SG-DEF-1977	Introduces labels and labeled points. Outlines the elements of parametric shape grammars.
	(*Above*) Marker-driven shape grammars based on an analogy to generative grammars. Grammars tend to be more tractable and easier to implement.	
	SG-DEF-1975	Based on two-dimensional rectilinear shapes. Implicit introduction to maximal lines. Mainly used to prove equivalence between shape grammars and other formal language formalisms. Emergent shapes are referred to as 'surprises.' Theoretical basis of the first shape grammar interpreter that properly took into consideration emergent shapes (Krishnamurti, 1982).
Subshape-driven shape grammars	(*Below*) Subshape-driven shape grammars. Progressively shy away from the generative grammar analogy. Grammars tend to be human-centered, less tractable, and harder to implement. Emergence is central to such grammars.	
	SG-DEF-1980	Introduces parametric shape grammar definition for shapes based on a maximal line representation. First definition for rule application explicitly based on the subshape relationship.
	SG-DEF-1991	Extends the definition to apply to shapes defined on different algebras, e.g., points, lines, planes and volumes. Introduces a being-alike function.
	SG-DEF-1992	Extends the algebraic definition to include weighted shapes. This definition subsumes a host of other independently defined weighted shape grammars, e.g., color grammars (Knight, 1989).
	SG-DEF-2006	Implicit definition of shape grammars considered in Stiny (2006). Essentially dismantles any vestiges of a connection to generative grammars. Indeed, generative grammars can be considered as a special case of shape grammars.

Unified backwards compatible definition that applies to both fixed and parametric grammars

For shape rule $u \rightarrow v$ and a configuration c, if $t(a) \leq c$, then the result of applying the shape rule on c is $[c - t(u)]+t(v)$, where t is a being-alike function, $\leq$ is a part relation, - is the operation of Boolean difference, + is the operation of Boolean sum.

Other investigations include theoretical studies on emergence, continuity, computational complexity, and decidability of shape grammar computation.

Recently, I have resumed my long-standing investigations into unsolved (theoretical) problems that relate shape grammar decidability to geometric constructability.

Sponsors

— Over the years parts of the work on shape grammars has been supported by various sponsors:

Science and Engineering Research Council (UK); The Open University; European Strategic Programme for Information Technology (ESPRIT); The Japan Research Institute; School of Architecture (Carnegie Mellon), the US Army Corp CERL-ERDC and the Netherlands Organization for Scientific Research (NWO) (support for Rudi Stouffs).

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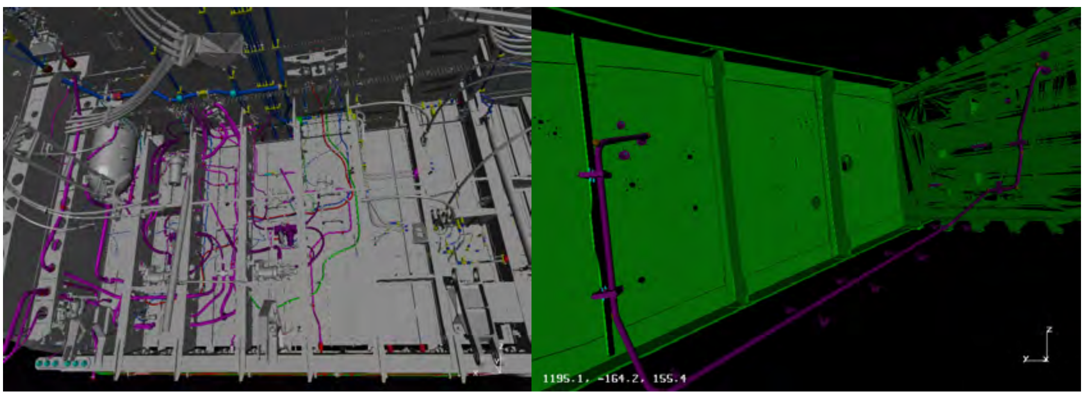
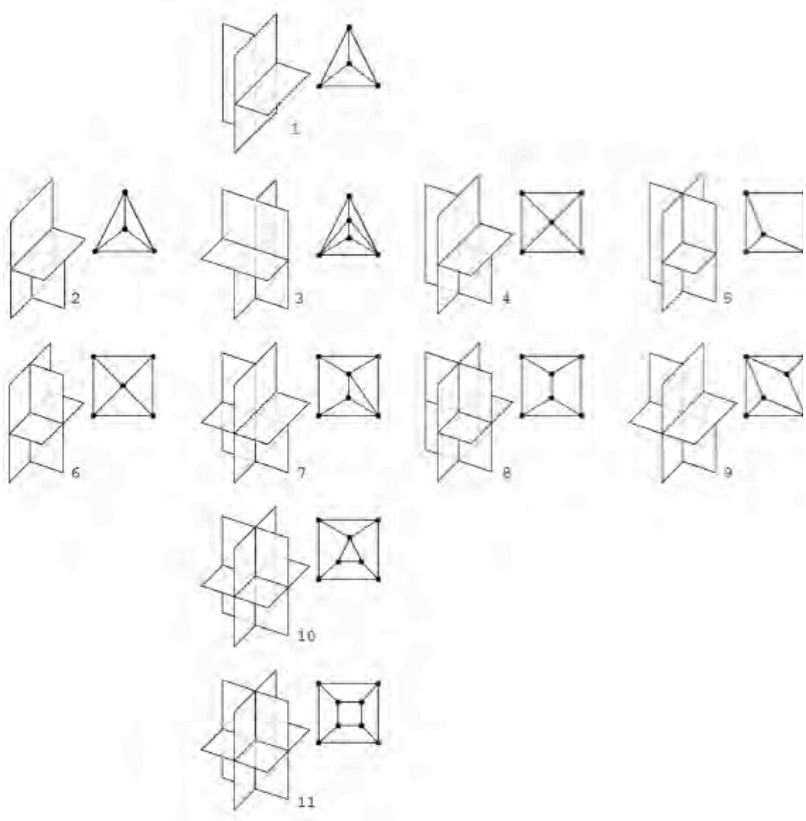


Piping in the landing bay of a Boeing 777 – example of grammars in real design – work of Jeff Heisserman

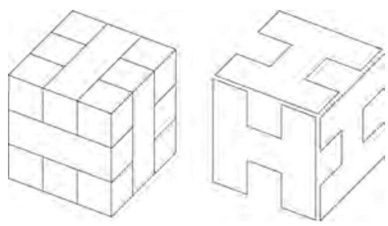
configurational studies

1975 —

I have long been interested in characterizing spatial designs with distinctive properties. My doctoral dissertation was on such spatial problems—in fact, on finding computational solutions to a number of otherwise hard to count generative problems, for example, finding connected arrangements of non-overlapping regions into a region with or without certain symmetry properties. Spatially, such configurations resemble layouts. The approach is to specify a provably correct algorithm to generate all possible designs that satisfy the constraints or requirements.



To the left are shown the possible interior joints formed when boxes pack into boxes without overlap. Joints of the kind numbered 1,2 and 3 produce boxes in which each cross-section yields an arrangement of overlapping rectangles within a rectangle in which lines do not cross to form a '+' shape and only meet at 'T's.
With appropriate perturbations all other kinds of interior joints can be made into one of these three.
If a configuration has a type 3 joint (called a ***lock***), then it contains interlocking volumes.
The smallest example is shown below.



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Rules to generate all possible arrangements of non-overlapping boxes within a box without locks