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Architecture, computing, and design assistance

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1. Spatial design for architecture

Design is one of the most complex of human endeavours requiring an enormous number of often conflicting criteria to be contemplated when identifying optimal solutions. Design is constrained by guidelines, codes, and standards applicable to the specific cultural and locational context that the design will be sited. Furthermore, a design has to be created within a collaborative team consisting of many professionals focused on specific subsystems and expert preferences that provide unique functionality to the overall design.

Architecture Design is a specific form of design concerned with the function-driven structuring of *empty space* — within architecture design, the majority of the considerations of *structural form* and resulting (*mal*)*function* are inherently spatial by nature. To manage the space of potential solutions a designer relies upon extensive training and experience in order to identify, manage, and resolve conflicting design criteria. Alongside expert ability and personal ingenuity, designers are supported by analytical and simulation tools, and rules of thumb which are based upon the precise physical properties of a design. The input and results of these tools and rules of thumb are almost exclusively quantitative, typically based on simulations of fundamental physical properties of a design. Few of these tools are focused on spatial design considerations supporting qualitative analysis within the *design space*, which is a style of analysis more closely aligned with the designer's mental model. *Next-generation design systems* will rely on representation and computational foundations that allow this form of design assistance to be created, and to build upon the traditional quantitative analytical support offered to designers.

In recent years, the field of *Construction Informatics* has developed as an applied science that studies the application of computer science methods and techniques for supporting the design, engineering, and construction of building facilities [24,19,17]. This includes 'hard computing' methods for solving numerical problems related to the simulation and analysis of physical phenomena, but effort has also been devoted to knowledge-centred approaches required to enable the representation, processing and exchange of design knowledge. Consequently, the application of *formal knowledge representation and reasoning* methods is emerging as a major field of study in Construction Informatics.

Building Information Modelling (*BIM*) as a sub-discipline of construction informatics has received increasing interest in both industry and academic communities over the last decades. The basic notion of BIM is an object-oriented approach to structure and share information generated for building and construction projects by a multitude of stakeholders covering its whole lifecycle. Being one among many aspects of BIM, a variety of geometric and topological information have always played a vital and integral role in the description of engineering artefacts. The increasing use and capability of software tools involved in the creation and processing of such spatial information has also led to elevated levels of complexity that spurred a need to structure, query and reason about multiple *spatial representations* of buildings and their components in new ways [4,8,10].

In order to facilitate interoperability among the heterogeneous domain-specific BIM tools used in a construction project, a vendor-neutral information exchange format is needed to allow uniform data storage instead of one-to-one mappings between individual applications. The *Industry Foundation Classes* (*IFC*) model, which has evolved from the broader Standard for the Exchange of Product data (STEP) initiative is fulfilling this role since its inception in the late 1990s. The models' capability to capture a wide range of different geometric and topologic representations has also made it a promising candidate as a native information model for spatial design support tools, for instance, as is also reflected by a number of contributions in this special issue.

2. Next-generation architecture design systems

Contemporary architecture design processes and tools regard eventual design products as isolated '*frozen moments of perfection*'.[1] Even within state-of-the-art design tools, aspects such as commonsense, semantics, structure, function, behaviour, people-centred design – concepts that are implicitly known to designers – are yet to come to the fore.

Next-generation people-centred design *systems*, *frameworks*, *assistive tools*, *educational aids*, and *design policies* necessitate foundational abstraction and computational building blocks where the modalities of human perception, action, environmental experience, and design conception and semantics are central. Research in this context addresses the following questions [6,7]:

- Contemporary Computer-Aided Archtecture Design (CAAD) tools provide robust geometric modelling methods; how can the future evolution of design computing bring notions of design semantics, structure, function, and people-centred design to the fore at an ontological, representational and computational level?
- What is the role of specialised forms of visual–spatial perception, abstraction, and commonsense spatial reasoning, within the broader realm of design computing, spatial design assistance, and tools for design learning and education?
- What is the nature and form of the assistive design feedback that designers and planners expect during the early design conception and iterative refinement phase? What are the implications of this from the viewpoint of the usability, interface, and interaction design aspects of spatial design (assistance) systems?

Research activities in the field of spatial cognition for architectural design are developing the cognitively driven foundational spatial

[1] This is an expression that occurs in a related context in the book 'Eating Architecture' (Pg. 12), ed. Jamie Horwitz, Paulette Singley, MIT Press (2004).

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informatics for people-centred architectural design systems [6]. The emphasis here is to develop human-centred models of abstraction, modelling, and computing for function-driven architectural design assistance [7]. The overall objective is to identify the manner in which interdisciplinary application of knowledge from computer science, cognitive science, environmental psychology, and architectural design may provide real benefit for the theory and professional practice of architecture, and eventually, tangible benefit for the quality of everyday personal life and work.

3. Architectural computing and artificial intelligence

The significance and the paradigmatic relevance of Artificial Intelligence in Modern Design are intertwined with Herbert Simon's original articulation of the *Science of Design* [23], and with Simon's interpretation of design as a "*decision-making process under constraints of physics, logic, and cognition*" [2]. This view of the scientific design process underlies much of what artificial intelligence has to offer by way of its formal representational and computational apparatus to the domain of design computing. From a topical viewpoint, the knowledge representation and reasoning area within artificial intelligence have been the cornerstone of most formal AI inroads in so far as problem-solving for design is concerned. In the last two decades, several interdisciplinary initiatives comprising of computer scientists, engineers, and designers have addressed the application of artificial intelligence techniques for solving problems that accrue at several stages of the design process: design conceptualisation, functionality specification, geometric modelling, structural consistency and code-checking, optimisation, collaborative (design) workflow management, design creativity, and a plethora of other issues.[2,3]

Analytical computing for spatial design, with its focus on spatial and semantic reasoning capability in design, is characterised in two ways: firstly, by the scientific questions that it must address from a representational and computational viewpoint and their relationships to the domain of artificial intelligence and design in general, and secondly, by the outcomes that a paradigm such as this is expected to produce. Specifically:

- the body of work that is concerned with the use of formal methods in knowledge representation and reasoning in general, and conceptual, geometric, qualitative spatial representation and reasoning in specific, for solving problems in modelling (e.g., spatial semantics, modularity, requirement constraints) and validation (e.g., diagnosis, hypothetical reasoning) in the domain of spatial design
- the body of work whose aim is to develop the generic apparatus – application framework, methodology, tool-sets – that may be used as a basis of providing people-centred design computing capability and assistive design support within a conventional CAAD-based spatial design and iterative refinement workflow.

The kinds of fundamental reasoning tasks that may be identified within the purview of spatial computing spans a wide spectrum, e.g., including reasoning patterns such as spatial property projection, spatial simulation, spatial planning (e.g., for configuration problems), explanations with spatial information (i.e., causal explanation, hypothetical reasoning) to name a few. Both within and beyond the range of domains identified here, these are inference problems that involve an inherent interaction between space, actions, events, and spatial change with the backdrop of domain-specific knowledge and commonsense knowledge about the world.

4. Assistive technology for design

Assistive Technology supporting planners, architects, and engineers in the design process consists of frameworks, toolsets, and specialised software applications that are able to check a concrete building design with respect to requirements and conditions. Significant scientific results have been achieved for formalising and checking rules which are based on a comparison of alphanumeric values of individual attributes, such as the thickness of a house's outer walls or a slab's thickness. However, the possibility to define and check rules that comprise conceptual design specifications, e.g., including qualitative spatial relationships between building components (e.g., topological and directional relationships), has been relatively recently investigated only by a few researchers. Assistive technology based on aspects such as *geometric and qualitative spatial representation and reasoning*, *conceptual reasoning*, and non-standard *complex data visualisation* techniques can help to facilitate the design task and support the designing architects and engineers. There are a number of important applications of spatial inference techniques in the context of building design and engineering:

- Design intent — assists the designer throughout the design task by recording and evaluating spatial design intent. Typically, this will be in the form of qualitative expressions of design function, such as the expected impact or *user experience* of a space, subjective lighting influences, flows between spaces, ensuring navigation patterns such that people do not get lost etc.
- Conceptual consistency — supports the detection of contradictions between individual requirements and/or regulations, i.e. checking the consistency of the effective constraints. If there are contradictions between different spatial constraints, the solution space for a valid building design may be empty. This has to be detected before the architect or engineer starts trying to fix his design, complying with one rule and violating another in an endless loop.
- Design consistency — used to check a concrete building information model for compliance with the client's requirements or with certain regulations. The latter refers to the vision of Automated Code Checking, which refers to validation of a building design for compliance with regulations and building codes. More broadly, this vision is closely related to the concept of people-centred functional design.

Achieving capabilities such as above require suitable ways for encoding conceptual requirements, design regulations, and building codes in a computer-interpretable manner. This particularly applies to spatial conditions which can be found at numerous places in construction regulations, empirical evidence-based studies, design guidelines etc. While there have been a small number of implementations of code compliance checkers, these are typically for structural engineering oriented prescriptive codes which are well suited to computerisation. With a trend towards more semantically rich conceptually grounded functional codes, there needs to be a refocused effort towards encoding the functional specifications and providing specialised constraint solvers compatible with these specifications.

5. About the special issue

This special issue resulted from an interdisciplinary '*design meeting*' held at *Schloss Etelsen* near the city of Bremen in Germany. Co-organised by the editors of this special issue, the meeting aimed at stimulating and facilitating an active exchange on interdisciplinary applications, ideas, approaches, and methods in the areas of:

- Design computing
- Design semantics
- Spatial cognition and computation

[2] The journal "Artificial Intelligence for Engineering Design, Analysis and Manufacturing" completed two decades of publishing in 2007 and its anniversary publication is a good overview of the area [12,15]. A sketch of '*40 years of design research*' is available in [3]. The collected works of [1,11,13,14,16,18,20] are a rich source of reference and contextualisation.

[3] The select works of the editors summarised in this article, e.g., [4,5,8–10,21,22], address many of these research topics more directly in the context of the questions that we raise in this special issue.

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- Spatial representation and reasoning (e.g., geometric, qualitative, visual and diagrammatic)
- Artificial intelligence for design
- Architecture and construction informatics
- Computer-aided architecture design (CAAD)
- Creative, functional, and people-centred design
- Assistive technologies for design
- Holistic spatial design.

We planned this meeting as a workshop in order to facilitate interaction between research communities that are addressing similar problems, and pursuing similar goals, but from different perspectives, and using diverse methods and approaches ranging from basic questions in computer science, to applied informatics and engineering research. The workshop solicited contributions from a range of disciplines and qualifications encompassing:

- Computer science
- Mathematics
- Architecture and construction informatics
- Civil engineering
- Cognitive science, and spatial cognition
- Environmental psychology.

One crucial goal of the workshop, and this resulting special issue, has been to identify interdisciplinary research synergies and collaborations spanning basic theoretical as well as applied research faculties. Our objective has been to inspire a direct interaction between the cognitive and computational sciences, and to promote the development of computation as a mechanism to materialise empirical results on design performance and function.

6. Contributions in this issue

After two to three rounds of manuscript revisions under the review of at least three reviewers for each contribution, five select publications have been accepted for this issue. The theme of knowledge-centred analytical and assistive technology, and spatial assistance systems for space analysis clearly comes to the fore, and resonates across all contributions. In particular, the five selected articles develop methods concerning:

- Knowledge-based computational methods in spatial analysis
- Design support specialising on mobility assistance
- Graph-theoretic design quality analysis
- Safety checking of automated construction models in relation to Building Information Models (BIM)
- Shape grammar based generation of parametric design systems.

Overall, the theme of "analytical design computing" and "spatial design assistance" resonates across all contributions. The representational and computational basis of the methods adopted range from semantic and knowledge-based specifications, to rule-based production systems and graph-theoretic formalizations. A brief discussion of the core aspects of the accepted contributions follow:

6.1. A knowledge-based framework for automated space-use analysis

6.1.1. Tae Wan Kim, Ram Rajagopal, Martin Fischer, Calvin Kam

Kim et al. propose a knowledge-based computational framework for automated space-use assistance to enable analysers to predict and update space utilisation whilst considering the three perspectives of space, users, and their activities. According to Kim et al.:

> "*there is a need for a logical framework in which analysers can gather, represent, and use the knowledge about users and spaces in support of automated space-use analysis.*"

> "*having a formal model that incorporates related information into space use analysis process is important because this model provides analysers with a consistent means of assessing and comparing architects' decisions about space-use.*"

Toward this, the authors operationalise concepts of *spatial computing for design* from the viewpoint of iterative refinement of designs, within a computational system for knowledge-based spatial design analysis.

6.2. Intelligent mobile assistant for spatial design support

6.2.1. Janusz Bedkowski

Bedkowski proposes a specific type of spatial assistance system involving semantic and qualitative spatial modelling and analyses for the mobile or indoor navigation case. As summarised by the author:

> "*The main idea behind the assistant is to create a semantic model of the environment and performing preliminary spatial reasoning to provide cognitive feedback. The main goal is to support the designer in his task by perceiving and evaluating spatial design intent.*"

The work by Bedkowski directly builds on the paradigm of spatial assistance systems, and reflects a close integration of concepts from the field of qualitative spatial representation and reasoning.

6.3. Automatic design quality evaluation using graph similarity measures

6.3.1. Barbara Strug

The contribution by Strug further represents the topic of spatial abstraction, iterative refinement, and design assistance. As Strug elaborates:

> "*Of special importance in the computer-aided design domain is the maintenance of spatial relations among different parts of the design. To preserve these relations an adequate representation is needed that could be used during both the design and evaluation process.*"

Strug uses hierarchical graphs to represent qualitative spatial relationships between building components and/or spaces. Strug applies the concept of graph kernels for assessing the similarity between two different building designs in order to support evolutionary design systems in finding good solutions. The proposed approach is illustrated by experimental results obtained for the task of floor layout design.

6.4. Build information modelling (BIM) and safety: automatic safety checking of construction models and schedules

6.4.1. Sijie Zhang, Jin-Kook Lee, Jochen Teizer, Charles Eastman

Zhang et al. analyse building information models with respect to spatial properties and relationships to automatically detect safety hazards and suggest preventive measures. A rule-based engine has been implemented on top of a commercially available BIM platform to show the feasibility of the approach. They state:

> "*From a safety management perspective, time and effort of safety engineers can be saved through an automated safety code checking and simulation tool that assists labor-intensive safety checking tasks.*"

As emphasised by Zhang et al., the developed automated safety checking platform informs construction engineers and managers by reporting, why, where, when, and what safety measures are needed.

6.5. Building envelope shape design in early stages of the design process: integrating architectural design systems and energy simulation

6.5.1. Vasco Granadeiro, Jose P Duarte, Joao R Correia, Vitor M. S Leal

Granadeiro et al. focus on the design assistance systems involving the integration of early stage building envelope design assistance with advanced stage building simulation focussing on energy performance of a design. The authors state:

> "*In the early design stages, when the envelope shape is defined, energy performance information is normally nonexistent, due to modelling for energy simulation being a time-consuming task…The methodology is based on establishing a direct link between early design generation, through a generative design system, and automated energy simulation.*"

whereas Granadeiro et al. focus on energy aspects, the general line of inquiry and their methods translate to other aspects of design performance, and serve as a prototype for a general framework for design performance optimisations.

7. Editorial postlude

The research initiatives that inspired the Design Meeting in Bremen, and also the resulting special issue, have been driven by a shared belief that architecture design systems need to take a big leap forward in their fundamental tenets, moving toward:

— a shift from point, line, polygon driven design processes into cognitively-driven computational modelling and reasoning about design semantics, structure, and function.

As working exemplars broadly supporting this line of thinking, we hope that readers will find the works described herein to be interesting, and that the integrative efforts and the scientific agenda of this issue will inspire other researchers to pursue projects and to further develop people-centred *analytical design computing* as an interdisciplinary and integrative interface for combining methods from computer science, architecture, construction informatics, environmental psychology, cognitive science, and spatial cognition and computation.

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