Experimental Design Methods – A Review
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ABSTRACT
Experimental design methods are applied in all phases of the design process and by almost every party involved in the design process. In this paper, we aim to give an overview of the background, applications, and technologies involved. A limited simple metric is introduced for assessing the degree of innovation. Future developments are outlined.
1. Sources of the digital (R)evolution

The introduction of the computer in the architect’s design office since the 1970’s has caused many changes. In general, most new technologies at the time of their introduction imitate existing techniques or shapes before their potential comes to full realisation. The same is true for Computer Aided Architectural Design (CAAD). The first generation of CAAD software in the architectural office can be characterised as the “electronic drawing board,” meaning replacement of manual draught labour to automated drawing production. It is no longer an issue whether CAAD “really” can support the architect. Nearly every architect’s office is using CAAD for normal production work. CAAD is now beyond the first round of imitating and supporting traditional practices, and there are major changes in architectural design prompted by the use of the computer. We can point out six main sources for the digital (r)evolution: handling complexity with information processing; new materials and construction techniques; rapid prototyping; versatile media use; communication and Internet; and Building Information Model. These are described in the following section.

1.1. Handling complexity with information processing

Although the almost ubiquitous presence of the computer in the architect’s office is a tremendous step, it is only the beginning. The architectural discipline has just recently begun rethinking itself – what it is that architecture is about, and some part of it involves the influence of computing on architecture. This is not a question of a new architectural style. It rather involves questions that before were too difficult to approach, too tedious to answer, or simply unimaginable. The use of the computer allows architects to investigate more deeply sustainability, intelligent energy use and resources management, complex shapes and production means, dynamic design teams, and the management of design information. All of these aspects revolve one way or the other around information, information management, and information transformation. These themes are also fundamental issues of computer science and information and communication technology (ICT). The application of these concepts in architectural design however is quite different from ICT. For example, architects increasingly are using analytical techniques that form the basis for finding the building design concept. An architectural office such as UN Studio (see Figure 1), uses elaborated graphic analytical techniques of the brief, from which they derive the concept for the building design.

1.2. New materials and construction techniques

The second major innovation of recent years in architectural practice is the introduction of many new materials and construction techniques. New materials such as transparent concrete, self-cleaning glass, new kinds of
plastics, printing techniques, etc. are expanding the range of material expression in buildings. In many cases, new materials mean also new details, construction order and techniques, and so forth. Architects are exploring different types of building cladding, interior materials, and roofing systems.

Computer controlled production machines for building products such as steel beams and panel systems not only speed up production but also enable precise production of many different components for roughly the same price (see [1],[2]). This means a shift from what is known as mass-production (industrial production of many similar objects) to mass-customisation (industrial production of many different objects). Figure 2 shows an example of custom-created limestone tiles of 70 x 70 x 3 cm³, by means of CNC milling.

1.3. Rapid prototyping

In the design office, small-scale computer controlled production machines are introduced in what is called rapid prototyping: 3D printers and laser cutters are the most well-known examples. These techniques are changing the role and timing of the use of physical scale models. The production of scale models by rapid prototyping is much faster than by manual techniques. This allows architects to take more advantage of the physical-tactile qualities of scale models. Because RP-models are created from digital models, a much tighter relationship between computer work and physical work is possible. By means of RP-techniques precise models can be created with less effort than before, which means they are less a diversion from the main design.
work. Since the digital model has to be created without flaws (or else it cannot be produced), the design process has to accommodate the creation of more precise models earlier in the design process [4], [5], [6], [7]. Figure 3 shows an example of a 3D print.
1.4. Versatile media use

The traditional media for the architect are sketches, scale drawings, physical scale models, and mock-ups. Switching between media allows the architect to understand the design in a different way. However, in order to switch between media, the work of creating the design in different media has to be done by the architect him- or herself. The computer allows switching between media more easily: 2D material can be scanned or exchanged in electronic format, drawings in the computer are printed, and 3D objects can be scanned and printed as well [8]. This brings about a tighter coupling of information that is stored in the various media, which can then be manipulated and tested (see [9],[10],[11],[12],[13]). Figure 4 shows a 3D scanner, used to digitise physical objects. A 3D scanner allows continued working in CAAD on the basis of a physical model.

1.5. Communication and internet

The design and realisation of a building is an effort undertaken by many people. Communication throughout the whole process is a crucial factor, and one which proves more than often to be a bottleneck. The various parties involved in the design and realisation process (including legislative bodies for permits and so) each have different requirements to the kind of information they need. This meant that each party had to copy, transform, and generate the new forms and information every time by hand. Apart from the cost and time involved in these processes, they were also prone to mistakes.

Before the use of Internet became widely adopted in the architect’s office, exchange of information took place through physical media – documents in mail or by fax, or sent on floppy disks, tape, or CD by mail.
Communication in this way between design parties is a bottleneck which is now removed for the better part by email and ftp-servers. Additionally, based on Internet technology many new applications have been created that allow immediate change of information, direct communication between CAAD software, and the availability of a lot of electronically retrievable information about products, maps, towns, architects, and so on. The computer in a sense has become the central point of information in an architect’s office, next to the normal stock of magazines, regulations, books, and documentation of earlier design projects. Figure 5 shows a visualisation of the Internet.

Figure 5. Visualisation of the Internet, image from website [15].

1.6. Building information model

One of the central challenges in CAAD from the very start has been the creation of a central digital design that all parties can access and modify. In recent years these efforts are now converging on the topic of Building Information Model (BIM for short). With BIM, which is still in development, information exchange becomes faster and easier. It means that parties can become more involved earlier in the design process, because information is earlier available. Figure 6 shows an example of the use of Revit.
2. Why experimental design methods?

Design methods range from relatively open-ended, loosely defined strategies to very descriptive stepwise procedures how to design a given object. A design method very often is based on experience of the architect. In those cases, they are usually implicit because architects seldom document their design process in a rigorous manner. The more formally defined design methods are typically found in handbooks – see for example [17],[18],[19] – and sometimes also in office regulations and manuals of large architect’s offices. In the case of handbooks, design methods can come from any design domain such as industrial design, mechanical engineering, software engineering, and so forth.

The purpose of a design method is to speed up the design process by indicating which steps should be taken, and in which order they should be handled. In short, using a design method avoids the risk that unfruitful paths are taken in the design process which cost time and force the architect or design team to return to earlier points in the design process. The second purpose of design methods is to act as a framework of agreement in a design team – using a particular method helps the team members to understand each others role so that they know what they can expect from each other. The third purpose of a design method is to have a framework of reference when an architect or design team is working out of their scope of specialisation or experience. This is for example the case when an office which usually deals in housing has to design a museum, or when an office becomes involved in a new kind of cooperation with design partners that they have not worked with before.

One important consequence that follows from the above is that design methods are very specific for a particular building type, kind of process, or way
of working. These aspects are not static, but can change – for example through
different building types that are introduced because of social-economic
developments, the introduction of asynchronous distant design teams in
collaborative design, and the introduction of the computer as a design tool. It is
important to notice that whenever one of these aspects changes, methods may
loose their applicability. This means on the one hand that methods have to stay
up to date in order to remain relevant, and on the other hand, that new
methods are continuously being created to meet changing demands on the
design office. Especially when there are many new developments going on, then
such new design methods are experimental (see [20],[21],[22],[23],[24],[25]).

There are currently a number of pressures on the Building &
Construction Industry (BCI) that are driving experiments in design methods:

• Design offices are under pressure to optimise efficiency in the design
  process so that it lowers the relative cost of creating a design. Design
  methods can be helpful to shorten the time it takes to create a
  design, they can decrease the amount of (re)-design, and they support
  faster creation of the design documentation.

• Manufacturers are using Information & Communication Technology
  (ICT) to deliver their product information, and to receive digital
  design information from the design office and create customised
  products for a design project (mass-customisation). CAM
  technologies are increasingly used to produce specialised products
  based on new designs.

• Design teams are becoming large with higher number of specialised
  members that have to coordinate their skills and knowledge. ICT
  makes it possible to have design teams with members from all over
  the world (distributed), who can work in different time-zones
  (asynchronous).

• Technological developments in the so-called Building Information
  Model (BIM) are driving towards comprehensive data models of a
  design that captures all the design and construction information of a
  building. Although BIM is still in the early stage of development,
  benefits of decreasing risk of information loss or distortion are
  already recognised by the Building and Construction Industry.
  Optimal use of BIM however asks for a different way of working
  from all design team members.

• Architect’s offices are recognising the use of experimental design
  methods as a means of profiling and marketing to set them apart
  from the competition. Another driving force simply is curiosity to
  find out the implications of new materials, styles, production
  techniques, and shape generation methods.

• The architectural theoretical discourse on the nature of architectural
  design is gradually acknowledging the influence of the computer.
  Architects/theorists such as Greg Lynn ([26],[27],[28]), Peter
  Eisenman ([29],[30],[31],[32]), and Ben van Berkel and Caroline Bos
As can be seen from the above, there are many different motivations for experimenting with design methods. Consequently, there is not one single “experimental” design method, but a very wide range of possible changes to the “traditional” design method. In the following sections, we aim to identify the areas, parties, and phases in the design process where changes may occur.

3. Areas of experimentation

Experiments are taking place in any number of areas that make up the design process. In order to clarify what exactly is being experimented, it is necessary to distinguish between the areas. We make a distinction between the following areas: communication, production, data model, simulation and prediction, visualization, teaching, and design teams (see Table 1):

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>Shared online documents for simultaneous or separate working; central storage facilities; chat-like direct communication techniques; digital on-site surveying and documenting; mobile phone technology.</td>
</tr>
<tr>
<td>Production</td>
<td>Computer Aided Manufacturing (CAM) techniques: Computer Numerically Controlled (CNC) production tools; file-to-factory information link.</td>
</tr>
<tr>
<td>Data model</td>
<td>Parametric design and Building Information Model (BIM) for models with interrelations between building elements; Industry Foundation Classes for general and exchangeable information structure; XML for custom-made data models.</td>
</tr>
<tr>
<td>Simulation and prediction</td>
<td>Physics-based models (Finite Element Method (FEM) for structures; Computational Fluid Dynamics (CFD) for air movement; radiosity for light simulation); construction process simulation (4D-CAD); people behaviour models for evacuation, activity scheduling, movement patterns, and experience; rapid prototyping for simulation of construction.</td>
</tr>
<tr>
<td>Visualisation</td>
<td>Virtual Reality (VR) for immersive 3D projection; rendering techniques for design presentation; data visualization; Human-Computer Interaction paradigms; augmented reality.</td>
</tr>
<tr>
<td>Teaching</td>
<td>Teaching methods and incorporation of design and computer techniques in the educational curriculum and design studios.</td>
</tr>
<tr>
<td>Design teams</td>
<td>24-hour design teams; collaborative design; integrated design; Computer Supported Cooperative Work (CSCW).</td>
</tr>
</tbody>
</table>

Application of the mentioned techniques in any of these areas can lead to experimental design methods. It is possible for example that one aspect is being changed while the other aspects remain the same and conventional. However, it is very likely that in those cases not the full advantage of the technique is used. In Table 2 we briefly summarise the likely impact of one aspect on the other aspects of the design process. The Table should be read horizontally, meaning “The impact of
Table 2. Likely impact of an aspect on other aspects of the design process.

<table>
<thead>
<tr>
<th>Communication</th>
<th>Production</th>
<th>Data model</th>
<th>Simulation Prediction</th>
<th>Visualisation</th>
<th>Teaching</th>
<th>Design Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>Documentation transfer; file to factory; direct consultation.</td>
<td>Reliable data transfer models; shared data models; increased exchange of design data.</td>
<td>No immediate impact.</td>
<td>Direct feed of data for visualisation techniques.</td>
<td>Online learning; communication via email and chat.</td>
<td>Internal and external communication in design teams; facilitation of group design.</td>
</tr>
<tr>
<td>Data model</td>
<td>No immediate impact.</td>
<td>Availability of design data for production tools.</td>
<td>Availability of design data for simulation and prediction.</td>
<td>Availability of design data for visualisation.</td>
<td>No immediate impact.</td>
<td>More versatile data exchange between team members; shared information.</td>
</tr>
<tr>
<td>Simulation Prediction</td>
<td>No immediate impact.</td>
<td>Testing via Rapid Prototyping of production principles.</td>
<td>Demand for more comprehensive data models that support simulation and prediction.</td>
<td>Availability of simulation and prediction results for visualisation.</td>
<td>Faster/shorter learning cycle to understand consequences of design decisions.</td>
<td>Earlier decision assessment; earlier involvement of other experts in the design process.</td>
</tr>
<tr>
<td>Visualisation</td>
<td>Visually more direct presentation techniques for designers.</td>
<td>Visualisation of production order.</td>
<td>Visual representation of geometry, relations, and derived aspects of the data model.</td>
<td>Visualisation of simulation and prediction results.</td>
<td>Learning of visualisation styles in design; communication of design results.</td>
<td>Visualisation of team member contributions and design team performance aspects.</td>
</tr>
</tbody>
</table>
Table 2. Likely impact of an aspect on other aspects of the design process. (continued)

<table>
<thead>
<tr>
<th></th>
<th>Communication</th>
<th>Production</th>
<th>Data model</th>
<th>Simulation</th>
<th>Prediction</th>
<th>Visualisation</th>
<th>Teaching</th>
<th>Design Team</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Team</strong></td>
<td>Demand for reliable, fast, affordable communication techniques.</td>
<td>No immediate impact.</td>
<td>Demand for exchangeable and robust data format between team members.</td>
<td>Demand for accessible, reliable, and robust simulation and prediction tools.</td>
<td>No immediate impact.</td>
<td>Provision of examples for teaching.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
communication on... production, data model, simulation and prediction, visualisation, teaching, and the design team.”

In the Table we aim to assess the impact of an aspect on another aspect, in the sense how it directly influences the other aspect. The degree of impact is not the same for all interactions – there is for example a difference in amount of impact between the influence of the data model on communication on the one hand and simulation and prediction on the other hand (strong relationship) and the impact of teaching on communication techniques (weak relationship). The latter is relatively low because the field of communication techniques is not looking a lot at teaching. Concerning teaching, it seems to be of more importance what the experience is that architects gain during their studies with communication techniques (see for example [35], [36] for such application in teaching). We can also notice that sometimes an aspect does not have an immediate impact on another aspect–such as the data model on communication. In that case, there is only an indirect effect since the data model supports communication but does not alter the nature of communication itself.

Generally speaking, we can observe two things: the first is that without exception each aspect is influenced by the use of ICT. This direct impact changes to some degree the way each aspect is handled. Secondly, each aspect also influences other aspects. Although it is possible to discuss such innovations in isolation (such as the use of ICT in simulation and prediction), we then miss the impact this has on other aspects of design. Because of this interrelationship, it is difficult to assess the impact of one single technology.

### 4. Actors that experiment

Experimentation in design methods is taking place by many different actors. These can be divided in three main groups: the Building and Construction Industry, software firms, and educational institutions (see Table 3). Although

<table>
<thead>
<tr>
<th>Actors that are experimenting with design methods</th>
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</thead>
<tbody>
<tr>
<td><strong>Building and Construction Industry</strong></td>
</tr>
<tr>
<td>Architect’s offices</td>
</tr>
<tr>
<td>Engineering &amp; consulting offices</td>
</tr>
<tr>
<td>Product developers</td>
</tr>
<tr>
<td>Real-estate developers</td>
</tr>
<tr>
<td>Production tool manufacturers</td>
</tr>
<tr>
<td><strong>Software firms</strong></td>
</tr>
<tr>
<td>CAAD software producers</td>
</tr>
<tr>
<td>Animation &amp; visualisation industry</td>
</tr>
<tr>
<td>Open source community</td>
</tr>
<tr>
<td>Research divisions</td>
</tr>
<tr>
<td><strong>Educational institutions</strong></td>
</tr>
<tr>
<td>Computer labs &amp; researchers</td>
</tr>
<tr>
<td>Academic networks</td>
</tr>
<tr>
<td>Professors in architecture</td>
</tr>
<tr>
<td>Students</td>
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</tbody>
</table>
there is a general tendency for all actors to innovate, it does not mean they have the same focus or interest because actors have different stakes which may not be compatible. Therefore, from a user point of view it is important to know who is driving a particular innovation, and from a development point of view to know for whom a particular innovation is intended.

4.1. Building and construction industry

The Building and Construction Industry (B&CI) concerns all actors involved in the creation of the built environment: architect’s offices, engineering & consulting offices, product developers, real-estate developers, and production tool manufacturers.

Architect’s offices

Small architect’s offices often are early adapters of new technologies (for example GL Form, Kolatan & McDonald, Eric Owen Moss). Experiments can also be identified in medium sized offices such as Morphosis, Gehry, Eisenman, UN Studio, and so forth. Large offices are usually slower to adopt new design methods because changes in process and communication involve for them many more partners and documentation than smaller offices. Nevertheless, large offices such as Foster Associates, Grimshaw architects, and Kohn Pederson Fox are also investigating new design methods.

Engineering & consulting offices

Engineering consulting offices have a stake in easier, faster, and more reliable communication with the other partners in the design process. This means they are looking at the data exchange formats to transfer designs (for example BIM), as well as the software tools they use for calculation and other work. A well-known example is the engineering office of Ove Arup & Partners.

Product developers

The stake of product developers for the Building & Construction Industry is to gain an increased use of their products in constructions. This means on the one hand good information provision to the designing offices, and on the other hand the development of specialised tools that work with their products. Product developers are looking in particular at IFC’s and Internet.

Real-estate developers

Real-estate developers usually create building projects (housing, offices, industrial buildings, etc.) for unknown future users. Their stake is to get
designs that will do well on the market. Once a project is underway, they need to get potential clients informed about the project. Real-estate developers therefore are investing in new techniques to acquire customer preferences for their products, as well as Internet techniques for information provision.

**Production tool manufacturers**

Production tool manufacturers make milling machines, rapid prototyping tools, laser cutters, etc. Their stake is to increase the use of these tools, which means they have to make them easily accessible both in handling, data communication, and price towards the Building & Construction Industry. In terms of using such tools, the Building & Construction Industry is a growth market compared to traditional markets such as automotive and aerospatial engineering.

**4.2. Software firms**

Software firms concern all those actors involved in the production and development of software: CAAD software producers, animation & visualisation industry, open source community, and research divisions.

**CAAD software producers**

CAAD software producers have a stake to serve their customers and to widen their influence so that they can increase their profit. This implies they have to balance between a certain amount of conservatism to enable existing clients to keep up easily with new developments and a certain amount of innovation to distinguish them from the competition and keep up with new technologies. They also have to position themselves between the demand for interoperability (that other software can use their data) and ownership protection (to remain a competitive advantage).

**Animation & visualisation industry**

The animation and visualisation industry is under a constant pressure to deliver in short time realistic animation and visualisation results. This demand is driven mainly by the entertainment industry for CG-rendered movies and computer games. Research institutes and large industries are also demanding increased performance for scientific and engineering data analysis and visualisation.

**Open source community**

The open source community creates software from a shared-development point of view. This section of the software developers often develops for perceived missing functionality or alternatives for expensive or inaccessible software.
Research divisions

Research divisions of institutes, industry, and firms have a stake to investigate or develop new technologies that will provide an advantage against the competition in the market. In many cases such divisions are internal and are not a very visible factor to the outside world. A notable exception is the Smart Geometry group.

4.3. Educational institutions

The educational institutions involve all those actors that teach students or professionals to become architects who are proficient in the use of CAAD: computer labs & researchers, academic networks, professors in architecture, and students.

Computer labs & researchers

Educational institutes have a stake to provide their students with adequate education so that they are well-prepared to enter the market or continue in research. Investment budgets are often quite modest, but on the other hand there is a lot of academic freedom to investigate many directions (see for example [37], [38], [39], [40]).

Academic networks

Researchers and teachers at educational institutes usually work in relatively small groups. Academic networks provide the communication infrastructure through which they can stay in touch with their peers and share their ideas and results. In the area of CAAD, these networks are eCAADe, CAADRIA, ACADIA, SIGRADI, CAAD futures, and ASCAAD.

Professors in architecture

At faculties of architecture, chairs for architectural design are often taken by professional architects who combine an architectural office with a teaching and research position at the university. The combination of practice and academic position allows them to experiment with new design methods outside of daily practice but within the architectural context of teaching.

Students

Students are taking up new technologies very fast, and while they are also in the process to learn design, they also often experiment with design methods. In particular design studios and competitions – such as FEIDAD – offer a platform where results of the work can be presented and compared among peers.
5. Experimentation in the building life cycle

The building life cycle consists of three major phases: the design phase, construction phase, and facility management phase. In the design phase, the building design is created as well as all the documentation that is required to realise the design. The design phase starts when the question for a new building occurs and a decision is taken to start a design process. In this phase therefore, we do not include preliminary activities such as feasibility studies, finding a building site, and so forth. A part of these activities belongs in the facility management phase (see Table 4). The task of the design process is to create a building design that will meet the demands of the client, conform to existing regulations, and meet existing standards of professionalism. According to [18], the design process consists of five activities that together with the resulting documents make up the “basic design cycle.” The activities are analysis, synthesis, simulation, evaluation, and decision. Consequently, we will use these activities in our overview as well.

In the construction phase, the building is constructed on the site. The construction phase comprises all activities that are necessary to realise the building. It starts with the creation of the building team and all the contracting activities, goes through the ordering or production of building components, via construction on site to final deliverance of the finished building to the owner. The construction process has three phases: preparation, resources management, and construction.

The facility management phase comprises the use of the building, including changes and refurbishment, as well as ultimate demolition. This phase contains all activities required to use a building and to maintain the usability of the building in functional, technical, and economical terms.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Experiments in the activity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analysis</td>
<td>Looking at the design problem; trying to find special characteristics that help create solutions. Looking at (partial) design solutions; trying to find strong/weak points; raising all relevant issues.</td>
<td>(Semi-)automated analysis, data-mining, graph and clustering techniques, analysis of interacting decision areas, Case-Based Reasoning.</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Create a (partial) design solution. Generate ideas and develop into solutions; integrate aspects into whole design solution.</td>
<td>Shape grammars, scripting, morphing, animation, cellular automata, L-systems, morphological box.</td>
</tr>
<tr>
<td>Simulation</td>
<td>Explore the future behaviour of the (partial) design solution.</td>
<td>Rapid prototyping, finite element analysis, computational fluid dynamics, people behaviour simulation, lighting models.</td>
</tr>
</tbody>
</table>

(continued)
Table 4: Activities in the building life cycle.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Experiments in the activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation</td>
<td>Value the (partial) design solution; decide on common way to appreciate (partial) design solutions; compare the outcome with requirements.</td>
<td>Bayesian networks, expert systems, fuzzy logic, multi-criteria analysis, conjoint analysis.</td>
</tr>
<tr>
<td>Decision</td>
<td>Decide whether a (partial) design solution is satisfactory or not; whether to proceed with next part of design problem, or whether the whole design is finished.</td>
<td>Decision support systems, multi-criteria analysis, conjoint analysis, data- and information visualisation.</td>
</tr>
<tr>
<td><strong>Construction phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preparation</td>
<td>(Sub)-contracting, costing, documentation.</td>
<td>4D-CAD to simulate and test the construction process, visualisation of the construction site organisation.</td>
</tr>
<tr>
<td>Resources management</td>
<td>Managing people, equipment, and materials.</td>
<td>Smart building components, on-site production.</td>
</tr>
<tr>
<td>Construction</td>
<td>Supervision, building, checking.</td>
<td>CNC milling, mass-customisation, augmented reality, total supervision stations, flexible monitors, robot construction.</td>
</tr>
<tr>
<td><strong>Facility management phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management</td>
<td>Assign spaces, maintenance, control, comfort, energy.</td>
<td>Sentient buildings, shape-changing buildings, heritage models.</td>
</tr>
<tr>
<td>Refurbishment</td>
<td>Changing existing parts of the building to accommodate for new demands; add or remove parts.</td>
<td>Space-function graphs, augmented reality, GPS-database link.</td>
</tr>
<tr>
<td>Demolish</td>
<td>Decision to move or leave the existing building; initiation of a new design project.</td>
<td>Building model to assist in setting up a new project brief.</td>
</tr>
</tbody>
</table>

5.1. Simulation as a design driver

Simulation is becoming increasingly robust, meaning that it requires less precise information to yield useful information, and it becomes increasingly user friendly, so that non-experts can use it as well. In the creative process of design, we can distinguish three main phases: analysis, synthesis, and evaluation. Traditionally, for simulation to work, it is necessary to create a special model of the design, after which simulation can take place (see Figure 7 left). With the new simulation techniques, however, creating an idea, model it, and simulate the model follow each other so fast that they become a fluent part of the design process (Figure 7 right). When the simulation model is used in such a way that it guides the design process, we can speak of a design driver (notion introduced by [41]).

Several areas can be distinguished in which simulation is taking this role: physics, behaviour, dynamics, performance, fabrication, and 4D (see Table 5).
Figure 7. Left: Traditional place of simulation. Right: Synthesis, modeling, and simulation as design driver.

Table 5. Examples of simulation as design driver.

| Physics | Simulation based on physical models of natural phenomena. 1) Radiosity calculates natural light distribution. 2) Computational Fluid Dynamics (CFD) simulates fluids and gasses by subdividing a space in smaller pieces, for each of which a set of equations can be set up for the fluid/gas behaviour and solved. 3) Finite Element Method (FEM) calculates stresses and displacements in a load-bearing structure by subdivision of a structure into small parts, solves equations for each part, and then aggregates all the results together. 4) A spring model uses masses connected with springs, usually for spatial relationship studies.
|----------------------------------|
| Behaviour | Simulation based on the behaviour of people. 1) Space syntax model of urban movement patterns. 2) Justified access graph which corresponds to degree of privacy in a building (complex). 3) Isovist model to indicate viewsheds in a plan to model sense of openness. 4) USSU - User Simulation of Space Utilisation model to predict daily use patterns in office buildings.

(continued)
### Dynamics
Simulation based on animation techniques. 1) Skeleton system connected to a surface by means of skin modifier - this makes the surface deformations more natural. 2) Dynamics by means of evolutionary techniques to created related-yet-different shapes. 3) The CADenary prototype tool uses chain models to interactively create load-bearing structures.

### Performance
Simulation based on the design, which is tested on a selected number of aspects. The degree of appropriateness (performance) on these aspects then steers the next generation of shapes. 1) Surface curvature optimisation. 2) Building envelope studies. 3) Structural system variants. 4) Facade elements organization.

### Fabrication
Simulation based on physical realisation of the design. This is typically studied by means of rapid prototyping in which the subdivision of the model to rapid prototyping parts has to anticipate the assembly of the model. 1) Milling machine that creates a physical model from a digital design. 2) Concrete wall with openings created by varying drills and angle of drilling.

### Table 5. Examples of simulation as design driver. (continued)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
<td><img src="image4.png" alt="Image 4" /></td>
</tr>
</tbody>
</table>

1. By author; 2. Lynn, image from website [48]; 3. Killian [49], image from application [50].

1-4. Gün [51], KPF New York.
Design drivers in this way function much in the way of primary generators as noted by [56]. Although simulation used in the fashion of a design driver or primary generator means that simulation gets a greater role in the design process, it is not the end-all application of simulation. It serves as a first and more rigorous investigation of a design concept, but it does not deliver all the required detail that a full-blown simulation can provide in the final stages of the design process.

6. A simple innovation metric

Given the many different phases during the building life cycle, the large amount of parties involved, and their various interests, it is clear that we are seeing a very fragmented set of activities. There is no single metric which can be applied to measure the degree of innovation in design methods. A very simple, however limited, metric to derive the degree of innovation, can be made by counting the number of aspects involved in a particular approach. These aspects are based on Party, Aspect, and Phase respectively.

1. **Party** – The party that is performing the experimental design method. The main categories of possible parties are: architect, (sub) contractor, advising engineer, and facility manager.

2. **Aspect** – In which aspect of design there is experimentation taking place. The possible aspects of design are: communication, production, data model, simulation and prediction, visualisation, teaching, and design teams.

3. **Phase** – The phase in the design process in which experimentation is taking place. These phases are: design (subdivided in analysis, synthesis, simulation, evaluation, and decision), construction (subdivided in preparation, resources management, and construction), and facility management (subdivided in management, refurbishment, and demolish).

The Party-Aspect-Phase distinction leads up to 308 different combinations (4 parties x 7 aspects x 11 phases). Since we are only concerned whether or not innovation or experimentation occurs, the total number of aspects is 4 + 7 + 11 = 22. A very simple comparison between experimental design methods then is based on counting in how different many aspects innovation occurs. This can be done in the following manner:
• For a given experimental design method, identify along the Party-Aspect-Phase aspects in which aspects an experiment is taking place. Consider each possible aspect as equally influential. Call the total amount of thus found Party-Aspect-Phase aspects \( i \).

• Establish the degree of innovation value \( D_{\text{innov}} \) by the following formula: \( D_{\text{innov}} = \left( \frac{i}{22} \right) \times 100\% \).

This metric is very simple and cannot be used for an in-depth indication of innovation, for the following reasons:

• It ignores all qualitative and quantitative differences between any Party-Aspect-Phase combinations.
• Because it simply counts the number of ‘scores’ on the Party-Aspect-Phase aspects, it ignores the interrelationships between aspects that we have seen earlier in Table 2.
• It counts each occurrence of innovation as equally significant; there is no weighting or other calculation of influence.
• There are no clear criteria to determine when something should be taken as experimental or innovative; therefore different people are likely to come up with different assessments of the same experimental design method. One has to be careful to state what kind of design method is considered as “traditional” or “conventional,” thus serving as benchmark for the innovative design methods.
• It cannot be fairly used to compare design methods from different time periods. Methods that once were considered innovative or experimental can become integrated into “mainstream” design and thus are no longer new. Therefore the metric can only be applied between design methods of the same time period.

It is necessary to note that a higher score of the metric does not necessarily indicate that the design product of that particular design method is more innovative than another one which has a lower score. On the contrary, it is very well possible to create innovative designs using less innovative design methods. The metric only indicates the amount of aspects that may be considered innovative or experimental – it says nothing whatsoever about the result.

The estimate therefore, can only be used as a first tentative indication of degree of innovation. It serves in particular when comparing two different design methods. Especially when a large difference can be noted the categories of the metric help with further investigation of the differences between two design methods.

6.1 New product profile visualisation

The New Product Profile (NPP) method is a straightforward ordinal comparison method to quickly detect the differences between products (15). In the NPP method, a matrix is created which has four columns and a
number of rows – the rows correspond to the aspects on which products are assessed. For example, if products are compared on comfort, price, and ease of handling, then the matrix has three rows. The columns have the values from left to right of –2, –1, +1, and +2. This corresponds with the scoring of respectively: “very poorly,” “poor,” “sufficient,” and “very good.” The user then for each product creates a new NPP, and fills for each aspect one of the scores. In this way, a profile is created that shows the strong and weak points of the product which can be compared with other products and their profiles. Because of its simplicity and visual character, the NPP method is suitable to visualise the Party-Aspect-Phase metric.

In order to maintain a clear overview, it is best to create for each design method three matrices: one for the Party component, one for the Aspect component, and one for the Phase component (see example below).

6.2. Example of comparison between three design methods

To give an impression of the application of the metric, we compare three design methods: one conventional (A), and two innovative (B and C). Method A is from a family house design case by LSL Architects (documented in [57] – Figure 8 Left), method B is from the Citron house design case by Greg Lynn Form [27] – Figure 8 Middle, and method C is from the Moebius house design case by UN Studio [33] – Figure 8 Right. All three cases concern the design of a family house of approximately the same size, and they are all from roughly the same time period (end of the 1990’ies).

Since the LSL Architect’s case concerns a conventional design, all aspects of Party, Aspect, and Phase score -2. Again it has to be noted that this value only measures the amount of innovative design methods, and not the quality of the design itself. Since we do not have documentation of the realization and management part, this is not taken into account in any of the NPP profiles of the Phase aspects. Concerning the Party aspects, neither case requires facility management, so this aspect is left empty. The Citron house case was a study by Greg Lynn alone, so no other parties are involved. Because of the experimentation with particle systems, skeleton systems, and building envelope [27], the case scores +2 in terms of experimentation. Similarly, UN Studio’s Moebius house is experimental for the architects.
because of the diagramming approach and moebius band principle [33]. In the Aspect profile we can see that the Citron house case scores high on Data model, Simulation and prediction, and Visualisation, which is similar to the Moebius house case which additionally scores high on Design team  

because of the network team approach (according to [33], 12 people from UN Studio were involved in the design process). Concerning the Phase profile, in the Moebius house case there is no simulation used contrary to the Citron house case.

<table>
<thead>
<tr>
<th>LSL Architects, family house</th>
<th>Greg Lynn Form, Citron house</th>
<th>UN Studio, Moebius house</th>
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<tbody>
<tr>
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<tr>
<td><strong>Phase</strong></td>
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Figure 10. NPP of Greg Lynn Form Citron house design case.

Figure 11. NPP of UN Studio Moebius house design case.
For the innovation metric, we simply count all cells that score +1 and +2 in the profiles. For the three design cases, the innovation metric is: LSL Architects family house $D_{innov} = 0$; Greg Lynn Form Citron house $D_{innov} = 36\%$; and UN Studio Moebius house $D_{innov} = 45\%$. The Moebius house design case scores higher because of the design team approach.

7. Impact on design methods

In the review above we discussed many techniques that are available today that may support or change design methods. As shown in Table 2 (Likely impact of an aspect on other aspects of the design process) there are many interrelationships between such aspects. As a consequence, a very wide range of innovations in design methods are possible — and it is impossible to list them all in detail. We may however outline a number of general trends that are taking place in experimental design methods based on the overview above.

- There is a shift from autonomous design generation towards user-assisted design generation. Strategic parts of the design are singled out to be handled with new techniques, while keeping the remainder of the design in more traditional ways. This changes the design method in such a way that criteria for identifying those parts and how to integrate them within the process are required.

- The development of robust simulation models that do not require precise input for simulation results allow early and fast testing of the performance of the design. In this way, a feedback loop can be started in which the shape of the building can be modified in direct response to an aesthetic or performance criterion. This is also known as performative design [58]. This changes the design method by giving more attention to the organisational logic of the design with respect to the performance criterion.

- There is a strong interest in the realisation aspect of a shape, in such a way that constructability aspect forms a consideration in the shape creation process. Rather than using standardised solutions, this strategy focuses on exploration of new production techniques — in particular mass customisation. This is also known as fabrication. This changes the design method by introducing a generate-and-test cycle that consists of design-realisation principle-mock-up making-design.

- The lifetime of a digital model is likely to extend across phases in the building life cycle - the so-called heritage model. Similarly as there are norms and standards for building documentation in the form of drawings, this means that there will also need to be a standard for the digital design model. Data management therefore, becomes an additional task of the architect. This is also required to support collaborative design and communication between design
partners. The design method changes to allow for more systematic and rigorous documentation of the design process.

- The processing power of the computer allows taking into consideration more knowledge and information that is useful for generating the design. Additionally, such processing will be required from the other partners in the design process as well as from regulatory bodies (government, municipalities, and so on). This will change the design method in such a way that different decision strategies to make design decisions will be necessary.
- The design model is no longer a single product of the designer’s office, but integrates information from various sources in particular via the Internet.

It is quite certain that we will see many more experimentations going on in the near and far future within architectural design. Through the innovation metric and its NPP visualisation a modest first step is taken to make these developments visible and open to comparison and discussion. Nevertheless, much work remains to be done to get a better insight in innovations that are taking place.

7.1. Acknowledgements

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