Learning from other Disciplines for Designing Technologically Enhanced Spaces

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In this paper we explore how design methods from different disciplines can be applied to designing technology-embedded, communicative spaces and how interdisciplinary transfer can be improved. We present design understandings from architecture, engineering, natural sciences, management sciences, and philosophy. Methods, principles, practices, and procedures from mechanical engineering, neuroinformatics and knowledge visualization are applied in handling complex tasks and in improving communication among different disciplines. We present first findings for fruitful cooperation and for transferring knowledge across disciplines.

Keywords: *Design Methods; Axiomatic Design; Design Axiom*

Introduction

From a historical point of view buildings corresponded to and were distinguished by their uses. Their design represented social divisions and structures, and made them visible. The buildings and their facades reflected organizations and social groupings. Modern information technologies provide several opportunities for simplifying and streamlining everyday's life, but are also changing the character of the built space. Since information technologies have radically different spatial implications than traditional arrangements architects are challenged to suit the role of architecture to the altered living conditions. The emergence of communication and information technologies leads to the development of smart environments, smart spaces, ambient intelligence, building intelligence, and intelligent spaces (Chiu, 2005). These hybrid environments, involving a mixture of analogue and digital data processes, will provide new ways of interaction with information and for communicating. One crucial task, therefore, will be to translate digital information into visual and auditory interfaces and make these interfaces part of buildings. Bringing computation into the real, physical world and embedding it into the built environment presents the challenge of creating spaces that are designed around human beings rather than technological needs. Not only the character and the design of the built spaces has changed but also the image and self-image of architects have changed dramatically for several years: Away from the theoretical design as central part of architecture towards building practices; away from questions concerning aesthetics towards questions concerning technique, adequate technologies, deadlines, and costs. It can be observed that the formerly autonomous master builder becomes a communicating and promoting building manager. He combines the aesthetic of architecture with systematic and functional approaches.

Background

Our newly founded Competence Center for Digital Design & Modeling (DDM) at the ETH in Zurich[1] aims to acquire a fundamental understanding of salient, domain independent principles and methodologies underlying design. Our goal is the definition of domain and discipline independent axioms in order to establish design as an independent scientific discipline, Design Science. The DDM couples the ETH's vast expertise in the fields of design and modeling beyond disciplines. The multidisciplinary organization consists of 25 research groups from 11 departments including architecture, physics, mathematics, computer science, electrical engineering, and philosophy. By learning and understanding what design means in natural science, engineering disciplines, and management science, and adopting these insights to architectural design, we investigate novel principles of design.

This provides the basis to explore how design methods from different disciplines can be applied to designing technology-embedded, communicative spaces and how interdisciplinary transfer can be improved. We believe that there is a profound need for architects and architecture students to learn more about how these technologically enhanced environments are best designed, how to create more insights by applying knowledge from other disciplines, and how to work efficiently with a range of stakeholders.

Research Questions

Since engineering systems, design tasks in architecture, and the relationships between given constraints have become more complex, conventional methods of design have reached their limits. Information and communication technologies change very quickly and become obsolete. In contrast, architecture has a long-term orientation and it is necessary to focus on the fundamentals of architecture. In the same way that our social and cultural trends change, the requirements of our living and business spaces have to be adapted. Therefore, it is difficult to specify long-term requirements and the human needs for spaces. Analyzing principles, practices, and procedures of design in disciplines outside architecture enables us to find methods and approaches for managing the complex tasks of bringing together aesthetics, creativity, human needs, technological requirements, restrictions, and economics.

The questions that arise and which we are currently finding answers to, are:

- How can we improve the transfer and communication of knowledge among different disciplines and stakeholders?
- What can architects learn from importing models and adopting design methods from other domains to better manage complex tasks like the design of technologically enhanced environments?
- How can other disciplines profit from architects' abilities and knowledge?

Design Methods

Design is eminent throughout different disciplines of sciences, engineering, management, and architecture. However, within these fields the definition of design and its understanding depends on the specific context and the field of interest. The most common understanding of a designer is that he is somebody with an idea who is concerned with the appearance of an object. Since the initial brain work usually remains unseen on the outside, design is mostly seen as a procedure related to material things. The significant difference between science and engineering is their different idea of design and development. Science concerns itself principally with the understanding of the phenomena of the world as they are. In contrast, engineering is concerned with solving humans' problems in applying scientific and technical knowledge. Engineering addresses the design of a solution to a practical problem using any

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available knowledge. Engineers deal with questions of how to solve a problem and how to implement the solution whereas scientists ask why a problem arises and attempt to explain phenomena. In doing so, scientists create mathematical models based on observations. Design in management sciences is among other things related to organizational design, business process design, and product design. Design in architecture underlies a targeted objective. Architectural design addresses feasibility and affordability as well as functionality and aesthetics. In philosophy the term design originally refers to technical models and processes supposedly related to the creation of our world as it is now by a designing God. Figure 1 shows a compilation of a set of design definitions in different disciplines. The list is not exhaustive.

The following approach seems to be common to all different design activities: First, the designer has to know and to understand the needs and ideas of the partner to be addressed. Afterwards, he defines what he wants to achieve and describes the requirements necessary to satisfy the needs. To fulfil the desired purpose concepts are set up through synthesis. Based on analysis, evaluation, and the decision to modify the proposed concept the design solution is optimized in multiple steps. Finally, the resulting design solution is checked against the requirements and needs that have been established. The last step is the final implementation and realization of the chosen design.

Axiomatic Design

The term Axiomatic Design was coined in the 1970s by Nam Suh, engineering Professor at MIT, and refers to a theory and methodology to decide on the best design for a targeted objective. Axiomatic design is a systematic approach to design and is considered as a functionally based system (Figure 2). Suh developed two design axioms which became the basic principles in engineering design. These axioms provide simple and compact rules for engineers to solve a wide range of design problems, e.g. airplanes, cars, machines, devices, products, processes, hardware, and software. An axiom is a statement that cannot be proven, that is always observed to be valid, and that is universal and generalized. Therefore, it can be applied to every process of decision making and any kind of design activity, ranking from the development of organizations and businesses to everyday mundane problems. Suh's axioms are considered as evaluation methods to provide a rational basis for finding the best solution or alternative for a design problem. The two design axioms to govern good design developed by Suh state the following (Suh, 1984):

Design Axiom 1: The Independence Axiom

This axiom claims that the independence of functional requirements must be maintained and maximized. Therefore, it deals with the relationship between functions and physical variables. The goal is to be able to create an independent and uncoupled design which is adjustable and controllable without iteration.

Design Axiom 2: The Information Axiom

This axiom claims that the information content of the design must be minimized and that the probability of achieving its functional requirements must be maximized. According to these axioms, thus, the best design among those ful-

	DESIGN
Architecture	■ Multi-layered, dynamic, and creative process ■ Interdisciplinary ■ Speculative ■ Underlies a targeted objective ■ Building materials ■ Addresses feasibility, affordability, functionality, and aesthetics
Engineering	■ Feed-back process ■ Decision making process ■ Meet a stated objective ■ Addresses functionality and feasibility ■ Establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation
Management Sciences	■ Concept and strategies development ■ Analysis ■ Implementation planning
Natural Sciences	■ Describe behavior of objects, processes, and phenomena with the help of natural laws
Philosophy	■ Production of symbolic structure to build an artefact serving a defined function

Figure 1
Understandings and definitions of design depending on the field of interest and specific context

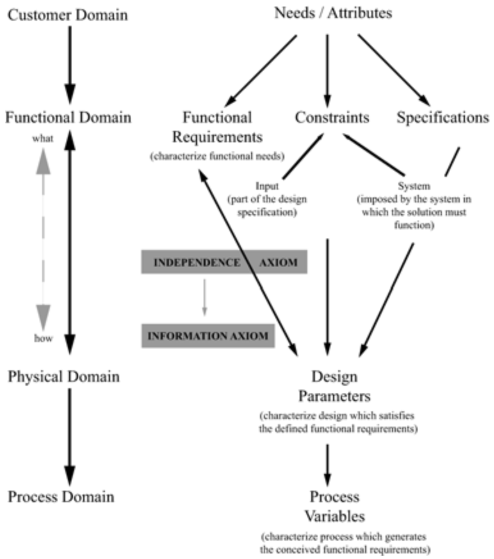

Figure 2
Axiomatic design process according to N. P. Suh. The design process is iterative in a sense that the process is not linear and the designer switches between the domains (Suh, 2001)

filling axiom 1 is the one with the smallest information content.

The functional requirements, characterizing the customer needs or the functional attributes of a product corresponding to the design goals, are mapped to design parameters. If there are more design parameters than functional requirements the design is either redundant or coupled. A design is considered to be infeasible when the number of functional requirements is greater than the number of design parameters. Functional independence should not be confused with the physical independence.

Today, axiomatic design is not just a theory. In fact, it is nowadays common in various companies such as Silicon Valley Group, Corning, Alcoa, Ericsson, and also in the automotive industry, for example at Ford, Mercedes Benz, Saab, Daewoo, and General Motors.

Approach

In our work at the DDM we observe and structure a set of principles and patterns common to all of the fields involved. Merging competence from different disciplines will exploit the synergies arising from interdisciplinary research. For that reason we bring together different schools of thinking which have been separated for centuries. Based on our research in building intelligence and global communication (Lang, 2004) as well as our profound background in architecture, and the existing knowledge within our competence center we are analyzing and finding out common grounds and differences in their understandings of the mechanisms and processes underlying design. The disciplines are covered individually and neutrally to obtain open-minded discussions. For that reason, we are able to exploit synergies arising from the disciplines involved and contribute in merging the vast amount of isolated knowledge sources. As a first success we achieved bringing together experts from natural sciences, engineering, architecture, and management to discuss about a fundamental understanding of design. In addition, leading researchers define their understandings of design and modeling within our colloquium "What is Design? What is Modeling". Furthermore, we have been holding workshops with the aim to find out whether there exists a common domain-independent understanding of design and if so how to formalize new design axioms to strengthen design science as a bridge between fundamental sciences, engineering, architecture, and business. Joint research and transfer projects together with partners form the industry allow us to tackle complex and difficult design tasks that demand interdisciplinary solutions faster, more efficient, more economic, and more satisfying in the sense of aesthetics and functionality.

In our research we investigate design methods, design principles, design patterns, and design grammars from different disciplines to gain a fundamental understanding of design. This enables us to find out how they can be transferred across disciplines. Applying them to suitable applications together with industry partners allows us on the one hand to verify our assumptions and on the other hand to assure the real world value of our findings. Designing technologically enhanced spaces we gain from our previous research in Tele

Reality, 3D Video, and Video Systems (Lang, 2005; Lang and Hovestadt, 2004). Cooperating with experts from neuroinformatics and building on results from research on living systems allows us to find further possibilities for the design of responsive environments. We found out that knowledge visualization helps to improve the communication among different disciplines and that axiomatic design supports teamwork in evaluating solutions more efficient.

Design Methods in Living Systems

Looking at living systems, nature is able to create extremely complex systems that are robust against mismatches in components, defects in construction, and failures of performance over large variations of operating conditions. The main difference to the conventional understanding of design is that living systems do not require an explicit designer. The traditional understanding of design assumes the existence of a designer external to the object. In contrast, biological systems are in order to be functional self-constructing, self-building, and self-assembling. This kind of self-design revives statements of cybernetics, opens up a new way of thinking, and can be used for the design and construction of contemporary architecture. Cybernetics is concerned with the similarities between autonomy, living systems, and machines. Later on it emphasized on self-organization, cognition, and the role of the observer in modeling a system.

To be able to borrow, simplify, and adopt nature's design it is important that we understand the natural design process better. Working together with researchers from neuroinformatics allows us to gain a deeper insight into living systems, and discover strategies for novel design methods. Living systems offer a huge variety of design relations and design principles. As a result, we believe being able to bridge the gap between the lifetime of information and communication technologies and built architecture.

Knowledge Visualization

A crucial and essential factor for investigating good concepts and designs for technologically enhanced spaces is the interdisciplinary transfer of knowledge. We have to find visualization forms which work across disciplines and allow transferring facts, insights, experiences, attitudes, values, expectations, perspectives, opinions, and predictions. These questions are investigated in knowledge visualization. According to Burkhard's definition, knowledge visualization examines the use of visual representations to improve the transfer and creation of knowledge between at least two persons (Burkhard, 2004). Knowledge visualization research identifies and assesses computer based and non-computer based visualization techniques that help in knowledge-intense processes, such as the transfer and creation of knowledge. For effectively transferring knowledge through visualization the following questions need to be considered: What is the goal of using a visualization method? What type of knowledge needs to be visualized? Who is being addressed? What is the best method to visualize this knowledge? Answers to these questions lead to first conceptual frameworks that are described in (Eppler and Burkhard, 2005). These frameworks can therefore be seen as a building block for investigating a common language in interdisciplinary research teams.

Challenges and Potentials

In investigating the aforementioned research questions we obtained the following first results regarding knowledge transfer, knowledge adoption, and knowledge impartment.

In order to create superior designs and human-centered notions instead of computer-centric ones architecture, axiomatic design, knowledge visualization, design methods in living systems, and technical engineering have to be combined. Axiomatic design helps to speed and facilitates the design process, and makes a contribution to team communication. Regarding design questions, discussions often tend to become irrational. Applying the systematic and functionally approach of axiomatic design allows team members to move from arguing in favor and to take up a strong approval of a specific design, to analysis, evaluation, and comparison of alternative design solutions. In addition, knowledge visualization supports the transfer and the communication of knowledge among different disciplines and stakeholders. We realized that some terms and notions as well as optimization criteria differ in parts substantially among the different disciplines and areas. Therefore, it is important to find a common language based on science and to understand the way of thinking used by different fields.

Traditionally, the architectural design process is often a mixture of intuition, experience, art, and analysis to create concepts and shape the humans' environment. To a large extent the design process follows a systematic approach. A crucial part of architectural design work is to catalogue observations made on site according to criteria. Basically there are four key categories: (1) Description of the site using morphological and typological approaches. (2) Description of the spatial system using the empirical method for analyzing space. (3) Description of programs, functions, and structures and generation of a system diagram to visualize the functions and their relations. (4) Description of symbol character and meaning. Many laypeople are unaware that architectural design is a multilayered dynamic process which requires multiple steps where each phase is a revision and progression from the previous one based on analysis, evaluation of the analysis, decision to modify the concept, and finally the creation of a new concept. They often believe that architectural design is scrawling on the back of a beer mat. To better communicate their course of action, their knowledge behind the design, and their design decision, architects should apply the systematical approach of axiomatic design. Admittedly, axiomatic design cannot be applied in a completely satisfactory way regarding economics and aesthetics. Concerning aesthetics it is difficult to define the functional requirements and most customers are probably not able to specify their needs. Since architects are by their nature creative and are trained to come to a design decision combining vague customer demands and aesthetics they could in return solve this deficit. Combing architects' skills to merge rational and quantifiable parameters as well as more intermediate and uncertain variables with the concept of axiomatic design provides a promising basis for the design of technology enhanced spaces.

Architects face complex tasks and considerations that are too complex to grasp as a whole. Therefore, they are capable of structuring information, thinking in networks and representing concepts, and to represent complex interrelations. For this purpose they illustrate their imaginations, ideas, concepts, and designs using different methods of representation forms taking a diversity of visualization methods into account. Furthermore, they translate customers' ideas and needs into functionally and visually appealing design solutions. Leading their audience to different representation types of the same possible set of information they represent their clients' interests to the outside. More over, by the nature of the architectural discipline which bridges basic science and engineering, many architects have the ability to merge rational and quantifiable parameters as well as more intermediate and uncertain variables. For proper building design and execution architects take knowledge of other disciplines into account, have close cooperation with a diversity of specialists, and need a high degree of organizational competence. Therefore, architects' ability to learn new concepts and skills rapidly and independently and their fluency in visual and verbal representations break new working ground for architects in industries such as communication, automotive, and electronics, and expand their role in strategic planning, communication processes, strategic marketing, application development etc.

Figure 3 summarizes the core contributions of architects to other disciplines we have found within our center. In addition, Figure 4 shows what architects can learn and adopt from the disciplines available at the DDM.

Contribution of the Architect to other Disciplines

- Ability and willingness to detect, to evaluate, and to implement users' and customers' needs
- Ability and willingness to evaluate and to adopt new insight from other disciplines such as materials, methods, processes, and systems
- Enthusiasm and willingness to tackle and to address problems apparently unsolvable
- Professional realization of information taking into account aesthetics, style, form, and design
- Open-minded about novelties, also from other disciplines
- Impact of function and design on user acceptance

Figure 3.
What can other disciplines learn from the architects' abilities and knowledge

What architects can adopt from others	From Whom
■ Systematic planning processes (rational approaches)	Engineering
■ Systematics and classification of functionalities	Engineering
■ Materials, tools, devices, methods, principles, ...	Engineering, Natural Sciences, Computer Sciences, Business Sciences
■ Criteria regarding user acceptance	Engineering, Psychology, Ergonomics
■ Requirement and functional specifications	Engineering
■ Cost benefit analysis	Engineering, Business Sciences
■ Considering environmental influences, validity barriers of standards, etc...	Natural Sciences
■ Cognition earning and cognition processes	Biology, Philosophy
■ Identification and formal detection of correlations and their illustration, modelling, and abstraction	Physics
■ Structuring of complex processes, controls, and decision making	Engineering, Business Sciences
■ Optimization taking into account given criteria	Engineering, Mathematics, Physics

Figure 4.
What architects can learn and adopt from other disciplines.

Summary and Conclusions

The aforementioned abilities, combinations of different disciplines, and successful teamwork are necessary for good design of technologically enhanced environments. Since the design of the human environment is the core area of architects it is important that they play a major role in the emerging fields of integrating new technologies into the living environment, such as Ambient Intelligence, Ubiquitous Computing, Disappearing Computing and the design of sensitive houses, digital environments, and intelligent buildings, as well as telecommunications services and applications as is being done for example by France Telecom, Philips, Siemens, and Deutsche Telekom Laboratories. Right now these areas are mainly covered by computer scientists, electrical engineers, and mechanical engineers. As the design tasks we are facing today become more complex, acting together leads to more satisfying solutions more quickly and efficiently. For fruitful cooperation with these disciplines the transfer of know-how and knowledge has to go beyond importing and exporting knowledge. In the long run the goal has to be that synergies between the disciplines should arise. The establishment of interdisciplinary design centers and schools such as the d.school at Stanford University show that interdisciplinary teams are gaining in importance.

In this paper we introduce how architects' skills, which bring different demands together, can be used in combination with research findings from other disciplines for the design of complex systems based on fruitful teamwork. We realized that an important aspect of collaborating between disciplines is finding a common language. From our first investigations common ground regarding design approaches has already emerged. Therefore, we are searching for potential new design axioms which will provide the basis for further investigations into transferring and combining design methods from one domain to other ones. The goal here is the development of non-reductive approaches for managing complex tasks. We hope that our research and findings will help us and others to further explore not only new ways of designing environments enhanced by information and communication technologies, but also to expand the definition of architecture outside the traditional realm.

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