COMPUTATIONAL DESIGN LEARNING: THE SMARTGEOMETRY CASE

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ABSTRACT

COMPUTATIONAL DESIGN LEARNING: THE SMARTGEOMETRY CASE

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Computational design has brought in novel concepts to architecture and design disciplines by an integration of interdisciplinary knowledge, tools and methods. Computational design learning has entered the curriculum of architecture, and gained significance over time. Experiential learning environments such as computational design workshops offer strategies for a better understanding of the contemporary needs of computational design learning. Smartgeometry (SG) is a computational design organization that operates through workshops of interdisciplinary teams. SG uses and teaches the state-of-the-art computational design tools and methods. Instead of teaching the novel computational design tools in an instructive manner, SG workshops focus on teaching complex concepts of computational design by using the potentials of these tools through personal discovery and experimentation. In SG, the interactions between individuals, the environment, tools and materials lead to various learning strategies such as learning-by-doing, constructivist learning and experiential learning. This research aims to explore the contemporary mechanisms and strategies for computational design learning through an in-depth qualitative analysis of the SG workshops. It is also aimed to identify the aspects that emerge during an experimental, rapid and interdisciplinary computational design process.

Keywords: Computational Design, Computational Design Learning, Smartgeometry, Interdisciplinarity

ÖZ

SAYISAL TASARIM ÖĞRENİMİ: SMARTGEOMETRY ÖRNEĞİ

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Sayısal tasarım, disiplinlerarası bilgi, araç ve yöntemleri birleştirerek mimarlık ve tasarım disiplinlerine yeni kavramlar kazandırmıştır. Sayısal tasarım, mimarlık eğitimi müfredatında zaman içinde yerini almaya başlamış, ve giderek önem kazanmıştır. Sayısal tasarım çalıştayları, güncel sayısal tasarım öğreniminin yöntemleri ve stratejileri konusunda örnekler sunmaktadır. Smartgeometry (SG), disiplinlerarası takımlarla çalıştaylar düzenleyen bir sayısal tasarım organizasyonudur. SG çalıştaylarında son teknoloji ürünü araçlar ve yöntemler kullanılarak sayısal tasarım öğrenimi gerçekleşir. SG çalıştayları, modern sayısal tasarım araçlarını bilgilendirici bir yöntemle öğretmek yerine bu araçların potansiyellerini açığa çıkararak, ve deneysel keşifler ve deneyimleme gibi yöntemler kullanarak sayısal tasarımın karmaşık kavramlarını öğretmeyi hedefler. SG'de, bireyler, çevre, araçlar ve malzemeler arasındaki etkileşimler sayesinde çeşitli öğrenim yöntemleri açığa çıkar. Yaparak-öğrenme, yapılandırmacı öğrenme ve deneyimsel öğrenme, bu yöntemlere örnek olarak gösterilebilir. Bu araştırmanın amacı, sayısal tasarım öğreniminin güncel yöntem ve tekniklerini, SG çalıştaylarının derinlemesine bir analizini yaparak keşfetmektir. SG çalıştaylarındaki deneysel, hızlı ve disiplinlerarası sayısal tasarım süreçlerinde meydana çıkan kavramların tespit edilmesi de ayrıca amaçlanmıştır.

Anahtar Kelimeler: Sayısal Tasarım, Sayısal Tasarım Öğrenimi, Smartgeometry, Disiplinlerarasılık

Nanos gigantum humeris insidentes.

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ABBREVIATIONS

SG	Smartgeometry

CHAPTER 1

INTRODUCTION

1.1. Research Motivation and Goal

Architecture has been under the influence of different disciplines throughout time. It is possible to observe the changes and developments in architecture and building industry both in its theory and practice. New theories on architecture brought in new aspects of spatial cognition, new methods of materiality, representation, and structural expression. However, it has been widely argued that the pace of adopting new technologies for the building industry is slower than the other industries. The large scale of the designed products, the high-risk associated with complex buildings and their permanence in time are considered as determinant factors in the avoidance of design experimentation.

The avoidance of high-risk experiments in the practice of architecture does not necessarily hold true on research and education of architectural design. Design education, as argued by Callicott & Sheil, seeks out the unfamiliar, the unconventional, and the methods of other disciplines.[1] Due to the increasing emphasis on computational design in architectural practice, computational design has also taken an essential place in the education of architecture.[2] For architects, computational design can be a method for reaching the technological innovations and applying interdisciplinary knowledge in architecture in a more profound sense, not only as a tool but also as a means for thinking. Although computational design is typically

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[1] Callicott, N., & Sheil, B. (2000). The Degree Laboratory: The work of Unit Six at the Bartlett School, University College London. In *S. Pilling (Ed.), Changing Architectural Education : Towards a new Professionalism* (pp. 60-71). London: RIBA Publications.

[2] Oxman, R., Oxman, R. (2010) New Structuralism: Design, Engineering and Architectural Technologies, *Architectural Design*, 80:4**;** 14-23.

taught instructively, there are many examples where experimentation is integrated into computational design learning.

Design studios are at the core of architectural education.[3] In contrast to instructive learning, which is based on explicit guidance, design studios enable experiential learning or learning-by-doing. The design studio offers the potential to provide a multi-layered and enriching learning experience, where the ideas, positions, and artifacts are actively realized rather than being described.[4] [5] Moreover, design studios differ from classrooms by involving a space for individual work that increases the responsibility of the architecture students.[6] Similarly, computational design education has certain methods to understand the concepts and methods of computational design and their application in architecture.

Computational design learning is provided not only by educational institutions but also by independent organizations. One of the essential organizations on computational design is *Smartgeometry* (SG). Founded in 2001, SG organizes workshops in different countries with international participants and tutors, to contribute to the computational design learning for architects. As a contemporary and self-renewing event, SG workshops present an overview of the computational design learning over the years. SG workshops, this thesis argues, are representative of computational design teaching, and the processes of the SG workshops can set a model for different aspects of computational design learning.

This thesis is motivated by the increasing need for integrating computational design learning in architecture and architectural education. To this end, this thesis aims to explore, understand, and conceptualize the contemporary aspects and strategies of computational design learning through a case study on the SG workshops. Before the

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[3] Schön, D. (1985). *The Design Studio*. London: RIBA Publications.
[4] Nicol, D., & Pilling, S. (2000). Introduction. In S. Pilling (Ed.), *Changing Architectural Education: Towards a new Professionalism* (pp. 1-21). London: RIBA Publications.
[5] McQuillan, T. (2005). Informed Architecture: Three Tensions. In E. Harder (Ed.), Writings in Architectural Education (Vol. 26). EAAE Prize.
[6] Ibid.

case study, a review of the existing literature on computational design and computational design learning is presented in Chapter 3: Literature Review. Afterward, the findings of the study on SG workshops are carried out to understand the existing approaches of computational design learning processes. Finally, a discussion is carried out according to the results of semi-structured interviews, participant observations and the other data sources in order to demonstrate the computational design learning strategies that are present in the SG workshops, and how those strategies and aspects are related.

1.2. Case Selection

For the case study of this thesis, SG workshops are selected as a representative of computational design education for several reasons. Firstly, SG workshops enable four days of dense computational design learning that can include many processes and produce many outcomes to be analyzed and discussed. Secondly, SG workshops are assumed to be valid cases due to the well-known institutes and companies of computational design that support SG, such as Bentley Systems, Autodesk, IAAC, University of Toronto, etc. Thirdly, the directors of the SG organization are the key figures of the academia and practice of computational design. Moreover, the key figures of SG from academia have extensive experience in computational design education. Finally, SG events have a long history since 2001, which allows the researcher to trace the changes in the agenda and the processes of the workshops.

An SG event is organized in a decided location -a university- per every two years. There is a committee of computational designers who decide on the theme of the SG event. Afterward, workshop proposals are made, and the committee selects the ten workshops that are found to be of highest quality and the most relevant with the yearly theme. Then, participant selections are published, and individuals from different countries apply to participate in one of the ten clusters, and a number of participants are selected. The workshops are conducted during the four days of the event, and the outcomes of the workshops are exhibited. Afterward, the ten workshops are recorded and published on the website of SG. Some of the tutors further use the workshop outcomes for future research projects.

There are a number of resources that are used for data collection in this thesis. First and foremost, the researcher applied to the SG 2018: Machine Minds in Toronto as a participant and was accepted to participate in one of the clusters. The researcher took an active part in the "Inside the Black Box" cluster. During the participation, the researcher obtained data from the participant observations. Moreover, she conducted semi-structured interviews with ten computational design experts. Besides the participant data, additional data were used. SG workshops are archived on its website, with edited videos which enable an understanding of the process. There is an extensive number of workshops to be analyzed and compared. Therefore, instead of studying a single case, SG workshops present multiple cases that constitute a richer data source to be analyzed together. In addition, SG workshop tutors and directors produce academic research that includes the SG workshops, which enable the accessibility of rich data from written sources. Overall, the multiplicity of data sources enabled a case study to be conducted in detail.

1.3. Research Questions

Considering the discussions on computational design education and the case Smartgeometry in the previous sections, this research addressed the following research question:

- *What are the aspects and mechanisms behind computational design learning for architects and how are those mechanisms conducted?*

In order to answer this main question, a number of sub-questions have been addressed as following:

Sub-Questions:

- *How are the SG workshops conducted using the computational design tools and methods?*

- *What are the aspects that have an impact on the computational design learning in SG?*
- *How do the aspects of SG workshops relate to each other and contribute to the computational design learning processes?*

1.4. Research Methodology

This thesis aims at exploring the contemporary aspects of computational design learning for architects. It addresses this goal by analyzing multiple cases that a representative computational design organization, that is Smartgeometry (SG), provides. The case study on SG workshops is conducted through qualitative research for this thesis due to the need for an in-depth investigation of complex phenomena and the relationships between multiple aspects. As a result, SG workshops are analyzed by the case study method using several data sources, including participant observations, semi-structured interviews, written documents and video recordings of the past SG workshops. The researcher participated in the SG 2018: Machine Minds event in Toronto, Canada, to collect participant data. During the participation to SG 2018, the researcher participated in a workshop and experienced the learning environment of the SG 2018. Afterward, the collected data was coded, and several themes, concepts and patterns were discovered. The data analyses were discussed in Chapter 5: Findings. A more detailed explanation of the qualitative research methodology can be found in Chapter 4: Methodology.

1.5. Limitations

This research makes the initial assumption that SG workshops have the capacity to represent the field of computational design and education to a large extent. SG workshops involve a significant variety of workshops in each event. A limitation of this research is that SG workshops may not extensively represent the field of computational design. The range of the workshop objectives may not be not enough to represent the complete range of topics that are discussed in the field of computational design. Moreover, there might be various educational methods that have not been observed in the SG workshops. The learners of SG are assumed to be all of the contributors, involving the cluster champions, experts and cluster participants. However, the interviews concentrated on the computational design experts. A more detailed analysis could be conducted with involving students to the interviews.

Based on the fact that SG organization is a pioneer in the computational design field with its contributors and workshops, this thesis assumes that SG workshops have the potential to represent the processes of computational design learning. Moreover, SG achieves to be international by organizing the workshops in a different location each year and by being open to participants from all the countries. This research also opens the way towards similar research work that can be pursued with the future SG workshops or workshops of different organizations in order to compare the changing topics and methods of computational design learning in detail.

1.6. Chapter Outline

This thesis is structured in six chapters. Chapter 1, *Introduction,* provides a brief introduction about the research objectives, case selection, research problems, research methodology and limitations of this thesis. Chapter 2, *Literature Review,* aims to discuss the development of computational design over the years with certain impacts from different fields of knowledge, and the changing methods and perspectives on computational design education for architects. Chapter 3, *The Case: Smartgeometry,* explains the reasons behind the selection of SG as a case study and discusses the aspects of the SG organization, community, and workshops. Chapter 4, *Research Methodology,* presents the qualitative research methodology of this study and includes the information about the data sources, SG workshops, and interviewees. Chapter 5, *Findings on Computational Design Learning in SG,* presents and discusses the findings on computational design learning in the SG workshops utilizing the data analyses, including the participant observations, semi-structured interviews, video recordings, and written sources. Chapter 6, *Conclusion,* discusses the results of the findings on computational design learning in SG and the relations between different aspects. In this chapter, the research process and the findings of this study are concluded, and suggestions are made for future study.

CHAPTER 2

LITERATURE REVIEW

2.1. Computational Design

Computational design has been shaped by the synthesis of interdisciplinary knowledge, tools and methods. "The intellectual foundation for the nature of computational design rests at a particular confluence of domains in fields that include, but are not limited to mathematics, computer science, systems science, biology and philosophy."[7] Computational design has a critical influence on complex design problems in contemporary architecture. With the development of design tools and methods by the new technologies, it is argued that architects' and designers' capabilities have been immensely extended.[8]

Algorithmic thought has always been present in architecture, even before the invention of computers. Mimicking natural processes and material computation influenced some architects such as Antoni Gaudi and Frei Otto, who explored visual and tangible properties of materials by physical model making.[9] Digital computation entered the field of architecture with the invention of computer graphics in the 1960s. In 1963, Ivan Sutherland developed the *Sketchpad* as his PhD thesis at MIT. For the architects then, computers were able to do all the technical works performed by an architect such as drawing hard-lines, checking the structural and programmatic requirements, and drawing perspectives. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems were also developing at that time. Simple computational design tasks were realized through computer simulations and three-

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[7] Menges, A., & Ahlquist, S. (Eds.). (2011). *Computational Design Thinking*. Chichester, UK: Wiley.
[8] Peters, B., & Peters, T. (Eds.). (2013). *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (Vol. 01, AD Smart). West Sussex: John Wiley & Sons.
[9] Tepavčević, B. (2017). Design thinking models for architectural education. *The Journal of Public Space*, *2*(3), 67-72.

dimensional dynamic computer models. Overall, it can be suggested that digital computation initially was introduced to the field of architecture due to its capabilities in visual representation, rapidness and optimization.

In the 1970s, one of the main concerns of the architects was rational problem-solving. Christopher Alexander advocated that as the computers generate the same results for the same calculations, designers can also bring the same results for the same design problems.[10] Alexander adapted the terms such as *hierarchy* and *divide and conquer* from computer science into architectural design.[11] Some techniques were borrowed from operations research and mathematical programming, within the functionalist paradigm of the Design Methods movement. In the time, design was compared with science. Logical and systematic methods of design were further studied by some key figures such as Herbert Simon, Nigel Cross and Omer Akin. Terms such as systemic enumeration of design alternatives and automated space layout have been discussed in the agenda of architecture. Collectively, these studies outline a critical role for optimization, automation and systematic thinking in architecture.

The integration of artificial intelligence to computational design and architecture can be seen as an early example of interdisciplinarity. Nicholas Negroponte's books "The Architecture Machine" (1970) and Soft Architecture Machines (1975) supported that the real future of computers does not lay in computer-aided design, but in computers that could think. Negroponte described experiments conducted at MIT on many aspects of human-machine interaction. According to Negroponte, "The industrial revolution brought sameness through repetition, amortization through duplication. In contrast, information technologies, soft machines, afford the opportunity for custom made, personalized artifacts."[12]

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[10] Magalhaes Rocha, A. J. (2004). Architecture Theory 1960-1980. Emergence of a Computational Perspective (PhD thesis, MIT, 2004) (pp. 30-98). Boston: MIT. Retrieved December 15, 2017, from https://dspace.mit.edu/handle/1721.1/28316

[11] Alexander, C. (1964). *Notes on the Synthesis of Form* (Vol. 5). Harvard University Press.

[12] Bruegmann, R. (1989). The Pencil and the Electronic Sketchboard: Architectural Representation and the Computer. In E. Blau & E. Kaufman (Eds.), Architecture and Its Image (pp. 139-155). Montreal, Canada: MIT

Systems theory and cybernetics had significant impacts on computational design during the 1970s. Systems were defined as ”sets of elements standing in interrelation”.[13] Systems theory brought in the bottom-up thinking to computational design by explaining that the interrelation between simple elements can constitute complex systems. On the other hand, cybernetics theory, introduced by Norbert Wiener, stated that mechanisms of a feedback nature are the base of teleological or purposeful behavior in human-made machines as well as living organisms, and social systems.[14] Gordon Pask, in his paper "The architectural relevance of cybernetics", compared the information processing power of computers with buildings. Pask envisioned utopic buildings that store information in memory and performs calculations besides helping out with daily chores.[15]

Linguistics was another field of knowledge that had major impacts on computational design. According to Chomskian linguistics, the grammar contains a system of transformations.[16] The reflection of linguistics to computational design can be seen in the work of William Mitchell. Mitchell merged design with computation and linguistics by analyzing many cases including the classical orders of columns and Palladian villa plans and proposing a grammar for each example, and generating various schemes according to the transformative rules of the corresponding grammar. Alexander used tree diagrams in his paper, to show the relevance of an architectural grammar with the structure of a sentence. [17]

Computational design was also influenced by various concepts of biology such as biomimicry, evolution and morphogenesis. The biological concepts have contributed to computational design thinking. Evolution was seen as a computation composed of

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[13] Bertalanffy, L. (1969). *General System Theory*. New York, USA: George Braziller.
[14] Pask, G. (1969). The Architectural Relevance of Cybernetics. In A. Menges & S. Ahlquist (Eds.), *Computational Design Thinking*(pp. 68-78), 2011. London, UK: Wiley.
[15] Ibid.
[16] Chomsky, N. (1972). *Studies on Semantics in Generative Grammar*. The Hague, The Netherlands: Mouton Publishers.
[17] Mitchell, W. J. (1990). *The Logic of Architecture, Design Computation and Cognition*. Cambridge, US: MIT Press.

genotype and phenotype, where the genotype is under evolution and phenotype is only the physical correspondence of the genotype, also known as its key. [18] [19] The term *emergence*, which means self-organization based on systems theory, biology and complex systems was involved in the agenda of computational design. Methods such as genetic algorithms and neural networks were used to “generate unexpected novel forms and recognize meaningful shapes.”[20] Emergent systems became very useful for the computational design processes that focused on the concurrency of formation, performance and materialization. [21]

During the 2010s, the convergence of form, material and structure progressed more by the advancements in material science and its applications in computational design. The effect of biological and scientific knowledge continued with the emphasis given on the term *morphogenesis*. Morphogenesis was defined as the “logic of form generation and pattern-making in an organism through processes of growth and differentiation.”[22] The formation process gained importance more than the output, or the form. Ultimately, it was argued that form is a derivative of natural behavioral formation and it emerges as an effect exclusive to its particular environmental template.[23] “Form as a performative, dynamic system emerges from principles based on the behavior of the material, methods of manipulation and assembly, and interaction with the environment.” [24] Form, material, structure and behavior were approached as a whole rather than being separate elements during the formation processes provided by computational models. According to Achim Menges, structural

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[18] Frazer, J. (1995). *An Evolutionary Architecture*. London, UK: Architectural Association.
[19] Bentley, P. J., & Corne, D. W. (2002). An Introduction to Creative Evolutionary Systems. In A. Menges & S. Ahlquist (Eds.)*Computational Design Thinking*(pp. 120-130), 2011. London, UK: Wiley.
[20] Kalay, Y. E. (2004). *Architecture's New Media: Principles, Theories and Methods of Computer-Aided Design*. Cambridge, MA: MIT Press.
[21] Carpo,M.(2013). *The Digital Turn in Architecture 1992-2012*. West Sussex, United Kingdom: John Wiley & Sons.
[22] Leach, N. (2009). Digital morphogenesis. *Architectural Design*, *79*(1), 32-37.
[23] N., Oxman. (2010). *Material-based Design Computation*(Phd thesis, MIT, 2010). Boston: MIT. Retrieved January 5, 2018, from https://dspace.mit.edu/handle/1721.1/59192?show=full
[24] Menges, Achim (2008). Integral Formation and Materialisation. In A. Menges & S. Ahlquist (Eds.)*Computational Design Thinking*(pp. 198-210), 2011. London, UK: Wiley.

and environmental performance should be in the design process rather than being "post-design optimization criteria."[25]

The contemporary computational design focuses on integrating different fields of knowledge in the design processes. Topics such as "renewable energy, passive environmental design strategies, low-energy techniques, life-cycle assessment, and integrated neighborhood and community designs are becoming increasingly important for computational design."[26] Some fields of knowledge such as machine learning and big data are being involved in computational design. It can be interpreted that the range of problems and the fields of knowledge that are covered by computational design is increasing and superimposing. There is also an increase in the "convergence of knowledge, disciplines and the agents that constitute the network of a computational design process over time."[27] In time, the knowledge and skills needed for computational design have augmented, and overall, there seems to be some evidence to indicate that this augmentation will continue in the long run.

2.2. Computational Design Education

Design studios constitute the core of design education and enable students to actively design, produce, and gain new knowledge through the process of designing. A constructionist approach is present in the design education. According to Dewey, constructivism theory in education indicates that knowledge is actively constructed by the combination of experiences with what is already known.[28] *Constructionism*, is derived from constructivism by Seymour Papert, and focuses on "learning-by-doing" that indicates the construction of knowledge by creating a sharable output.[29]

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[25] Ibid.
[26] Peters, B., & Peters, T. (2018). *Computing the Environment: Digital Design Tools for Simulation and Visualisation of Sustainable Architecture*. John Wiley & Sons.
[27] Deutsch, R. (2017). *Convergence: The Redesign of Design* (Vol. 05, AD Smart). West Sussex: John Wiley & Sons.
[28] Martinez, S. L., & Stager, G. (2013). *Invent to Learn: Making, Tinkering and Engineering in the Classroom*. Torrance, CA: Constructing Modern Knowledge Press.
[29] Halverson, E. R., & Sheridan, K. (2014). The maker movement in education. *Harvard educational review*, *84*(4), 495-504.

Constructionism supports that learning occurs by the learner through the "building of knowledge structures".[30] Therefore, it is the act of making or doing that contributes to the learning, instead of an abstract knowledge transfer between a teacher and a student. Architectural schools have been contributing to curricular learning of computational design within instructive classes and experiential digital design studios. *Curricular learning* means that learning is planned with a set of objectives, methods and strategies through textbooks, various tools and examinations.[31] As the design education, computational design education can also be seen within a constructionist approach through learning-by-doing.

Computational design education entered to the architectural curriculum by the instructive courses on computer-aided-design (CAD) and computer-aided-manufacturing (CAM) tools, which were considered to have potential of changing and fastening the architectural production. The potentials of computational design on changing the ways of design process and design thinking were considered later.[32] Algorithmic thinking, understanding of the natural formation processes, and gaining interdisciplinary knowledge of design processes are just some of the competences that computational design education could provide. Key architects and design educators started to perceive computational design as one of the most significant skills for designers and architects around 2010s. Oxman advocated that scripting and tool-making have the potential of becoming the *core knowledge* in research, education, and practice of design.[33] According to Burry, "scripting is an essential component of 21st-century design education, and the design schools should ensure that all students emerge with sufficient scripting experience."[34] Scripting and computational design

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[30] Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism, 36*(2), 1-11.
[31] Havnes, A. (2008). Peer-mediated learning beyond the curriculum. Studies in Higher Education, 33(2), 193-204.
[32] Akin, O. (1991). Computational design instruction: toward a pedagogy. In M. McCullough, W. J. Mitchell, & P. Purcell (Eds.), *The Electronic Design Studio: Architectural Knowledge and Media in the Computer Era* (2nd ed., pp. 301–316). Cambridge, MA: The MIT Press.
[33] Oxman, R. (2017). Thinking difference: Theories and models of parametric design thinking. *Design Studies, 52,* 4-39. Retrieved from https://doi.org/10.1016/j.destud.2017.06.001.
[34] Burry, M. (2011). *Scripting cultures: Architectural design and programming*. John Wiley & Sons.

education were not only required as a technical ability, but also for deeper social aspects such as encouraging participation, supporting interdisciplinary collaboration and communication.[35]

It was argued by some of the computational design educators that computational design thinking requires the education of computational design tools. Computational design involves a major use and linkage between symbolic and analog representation. Symbolic representation was explained as the abstract mathematical relationships between physical entities such as the mathematical formula of force, while analog representation was defined as the depiction of objects the same way in physical reality, such as sketches, drawings, and three-dimensional models.[36] Aish and Hanna argue that the optimal way of designers and architects to engage with computation is through visual programming software that enables the consistency between symbolic and iconic representations.[37] "Visual programming languages involve certain abstractions that are needed for the familiarity with the real world because a computational designer needs to be engaged with physical phenomena as much as virtual phenomena."[38]

Learning-by-doing is an essential method of constructionist pedagogy that encourages the use of new tools, materials and technologies for producing artefacts. According to constructionism, by making and doing the artifacts, individuals can construct knowledge and experience the making process and learn better.[39] It can be commented that learning-by-doing provides experiential learning as it involves an active production process rather than a passive knowledge transfer. In design education, learning-by-doing is provided by digital and physical fabrication. "The use of specific

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35 Ibid.
36 Akin, O. (2001). Simon Says: Design in Representation. *Unpublished manuscript, School of Architecture, Carnegie Mellon University, Pittsburgh, PA. Retrieved from http://www. andrew. cmu. edu/user/oa04/Papers/AradSimon. pdf.*
37 Aish, R., & Hanna, S. (2017). Comparative evaluation of parametric design systems for teaching design computation. *Design Studies*, *52*, 144-172.
38 Ibid.
39 Blikstein, P. (2013). Digital fabrication and 'making'in education: The democratization of invention. *FabLabs: Of machines, makers and inventors*, *4*, 1-21.

tools and programs in formal and informal learning spaces are instantiations of Papert's constructionism and project-based learning also emphasizes learning-by-doing."[40] For instance, *The Design Factory Global Network* focuses on the use of maker spaces, fab-labs and research facilities. In METU, one *design factory* exists where learning-by-doing and experimentation is supported through the use of technology.

Extracurricular learning provides life-long computational design learning for students and professionals. Computational design workshops that cover a wide range of contemporary subjects can be relevant examples of extracurricular learning. The workshops are seen worldwide and usually conducted within conferences or short-term courses. Significant architecture schools organize short-term workshops on computational design in which the use of new technologies is promoted, such as the AA Visiting schools. Besides the institutions, associations and organizations contribute to life-long learning. For instance, Association for Computer Aided Design in Architecture (ACADIA), Education and research in Computer Aided Architectural Design in Europe (eCAADe) and The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) conduct annual conferences and workshops on computational design. ACADIA and eCAADe involves two days of conferences and two days of workshops, with the option of six workshops in ACADIA and two workshops in eCAADe. On the other hand, CAADRIA is a four days event that intertwines the workshops and conferences, and the participants can be involved in all of the ten workshops. Smartgeometry (SG) is also one of the most significant computational design events in which the workshops take four days and conferences take two days. Overall, SG is a longer event that gives weight to the workshops and *experiential learning*.

[40] Halverson, E. R., & Sheridan, K. (2014).

Experiential learning theory supports that learning is achieved by experiences and ideas that are formed and re-formed through experience.[41] According to Piaget, intelligence is formed by the experiences, which involves the interactions of an individual with his/her environment.[42] Experiential learning, similar to constructionism, supports that learning is achieved through the accumulation of experiences, which are used for knowledge making and learning from experiences. Experiential learning is related to the context of an individual and the surrounding entities can be related by the learner. As memorizing the situated experiences is an easier process due to the various associations between the memories, experiential learning may provide the gained knowledge to be more memorable than instructive learning. While instructive learning tends to give primary emphasis to the "acquisition, manipulation, and recall of abstract symbols", experiential learning focuses on the importance of "experience, perception, cognition, and behavior."[43] For that reason, experiential learning is an essential part of the design education. According to Willey, experimenting enables individuals to acquire their own experience and to synthesize this experience creatively during the design process.[44]

In parallel with the technological advancements, many organizations and extracurricular learning environments for computational design have emerged. Existing research focuses on singular case workshops or courses and the outputs are presented as the learning outcomes of the students. It is possible to track the agenda of computational design from the mentioned organizations. However, there has been little discussion on the computational design learning through multiple workshops of an organization. Although the studies on a single workshops examine the learning outcomes of students in detail through a single project, they do not necessarily represent the computational design learning in a general sense. Depending on the

[41] Kolb, D. A. (2015). *Experiential Learning: Experience as the Source of Learning and Development* (2nd ed.). Upper Saddle River, NJ: Pearson Education.
[42] Ibid.
[43] Ibid.
[44] Willey, D.S. (2005). Architectural Education in the Digital Environment. In E. Harder (Ed.), *Writings in Architectural Education* (Vol. 26). EAAE Prize.

topic, a single course or a workshop may lack some aspects of computational design learning. This study aims to contribute to the literature on computational design learning and architectural education by exploring the methods and strategies of computational design learning through an in-depth qualitative investigation of multiple workshops from multiple data-sources. As it presents the planned and emerging learning strategies and outcomes through investigating a variety of workshops of SG, which is assumed to represent the extracurricular computational design education, this study has important implications for computational design learning for architectural education and practice.

CHAPTER 3

THE CASE: SMARTGEOMETRY

3.1. Background

Smartgeometry (SG) is a computational design organization for architects, and it is open to participants from different disciplines. SG have been organizing events that involve workshops and conferences since 2001. There are several reasons behind the selection of SG as the case study in this thesis. Firstly, SG workshops are directed by an organization which is formed by the key figures of the contemporary computational design. Secondly, SG workshops are conducted for computational design learning. SG is also a relevant case by being an experimental and short-term event that enables experienced specialists to come together and conduct workshops. Besides, SG provides the adaptation of tools and knowledge from various disciplines to computational design while researching on certain design problems. These factors make SG a representative of the computational design research and education.

For SG workshops, the development of tools is as essential as using the tools for research and design activities. SG members agree that "for new design solutions, new tools must be created as existing tools are rarely producing new solutions,".[45] Tool development in SG is achieved by interdisciplinary knowledge synthesis, and design is accomplished by using the developed tools. While the significance of computational design tools for SG is widely discussed, the role of designing is not less important. According to the SG directors, "the research conducted at SG workshops is led by design, and always new threads running through the design process are sought, and their exploration is promoted for a thoughtful reflection and application in new design

[45] Peters, B., & Peters, T. (Eds.). (2013).

futures."[46] SG workshops involve the iterative cycles of producing and evaluating. This process is observable both in design and research, as ideas are generated with evaluation; therefore, generated ideas are disseminated.[47]

According to the SG director Rob Woodbury, while few architecture firms invest in novelty, students and researchers are more interested in research and innovation.[48] Woodbury commented that architecture and its supporting technologies co-develop and produce the rapid change in the discipline. In its early years, SG was seen as an organization that uses and develops computational design systems that support architectural design. However, recently, SG has become an experimental computational design workshop that integrates interdisciplinary knowledge to architectural design tasks. SG was explained as,

> "Academics and graduate students have been involved in design, review and trial workshops to an extent unusual for a corporate project. The existence of a motivated, independent user community and a relatively open and relatively well-resourced system development process provides opportunities for early and frequent verification of design choices."[49]

On its first years, SG events focused on solving complex geometry problems of architecture by using computational design tools.[50] The projects were individual, and the participants were mostly from practice. The events took place in hotels that provided space for conferences and individual working, as shown in Figure 1. Over time, with the increase in the involvement of academia and the new infrastructural settings provided by the universities, SG workshops have become more

[46] Mueller, V., & Smith, M. (2013). Generative Components and Smartgeometry: Situated Software Development. In B. Peters & T. Peters (Eds.), *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (Vol. 01, AD Smart, pp. 142-153). West Sussex: John Wiley & Sons.
[47] Stappers, P. J. (2007). Doing Design as a Part of Doing Research. In R. Michel (Ed.), *Design Research Now* (pp. 81-97). Birkhauser Verlag AG
[48] Woodbury, R. (2010). *Elements of Parametric Design*. Oxon: Routledge.
[49] Aish, R., & Woodbury, R. (2005). Multi Level Interaction in Parametric Design. In *Smart Graphics 5th International Symposium* (pp. 151-162). Frauenwörth Cloister: Springer.
[50] Peters, B., & Peters, T. (Eds.). (2013).

interdisciplinary, collaborative and experimental. The increase in the number of participants resulted in formations of design groups –that are called clusters- per each workshop. Since 2010, SG workshops have started to take place in design schools that have flexible open spaces –design studios- that provide both individual and collaborative working, as seen in Figure 3.2. Participants from academic backgrounds started to take part, interdisciplinarity, and complexity of the workshops have increased and individualism left its place to collaborative working. The change from 2003 to 2013 was described as;

> “The nature of the workshops has evolved from being largely a geometric and algorithmic pursuit to one about performance and feedback explored through physical prototyping. SG has moved from the computationally abstract to the tangibly real while, ironically, shifting from problems derived from real projects to more abstract pursuits of pure research.”[51]

Figure 3.1. SG 2009 San Francisco, California, in Palace Hotel[52]

[51] Mueller, V., & Smith, M. (2013).
[52] [SG 2009 San Francisco, California, in Palace Hotel]. (2009). Retrieved from https://www.smartgeometry.org/sg2009-sanfrancisco

Figure 3.2. SG 2010 Barcelona, in Institute for Advanced Architecture of Catalonia (IAAC)[53]

Since 2013, the transformation has continued. As Volker Mueller and Makai Smith stated in 2013, "computational design became a search for ways to expand the scope of what may be represented computationally."[54] From 2013 onwards, this scope has expanded even more. More fields of knowledge are influencing the research problems of SG and interdisciplinarity is gaining critical importance. SG workshops have evolved from a problem-solving approach into an experimental approach.[55] The most recent SG events take place in academic environments with the participation of various specialists internationally. "SG workshops work with many creative combinations and trial-error cycles; which gives the exploratory characteristic to it."[56]

SG provides a learning environment not only for students but also for experts. The workshops provide an emergent learning environment that is formed by the processes and the interactions between participants, tutors, environment, tools, and design outputs. SG workshops do not only teach computational design tools but also teach computational design thinking by interdisciplinary knowledge sharing. It can be argued that knowledge sharing across a community of computational designers in

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[53] [SG 2010 Barcelona in IAAC]. (2010). Retrieved from https://www.smartgeometry.org/sg2010-barcelona
[54] Ibid.
[55] Peters, B., & Peters, T. (Eds.). (2013).
[56] Salim, F., Jaworski,P. (2013). Exploring Human-Computer Interaction in Design Process. In B. Peters & T. Peters (Eds.), *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (Vol. 01, AD Smart, pp. 166-175). West Sussex: John Wiley & Sons.

addition to the four days of SG clusters, is a significant source of learning in SG. An explanation about this aspect of SG is as:

> "The group is dedicated to educating the construction professions in the new skills which will be required to use the new computational design systems effectively...The group conducts a series of schools and seminars where this new technology is explored in the context of highly experienced professionals."[57]

Rob Woodbury underlines the importance of computational design education and the competence of coding and being aware of the new technology. SG directors were mostly concerned about the technical abilities and computational skills in the past. Whereas, in 2018, the technical abilities became secondary concerns. Primary concerns of the present SG is to integrate different skills, disciplines, knowledge, people, and tools. [58] SG contributes to the field of computational design by its educational values that enable learning through an extended set of workshops, which embody a larger domain than architecture.

SG workshops present research environments that support scientific approaches, learning, and critical thinking. Since 2010, SG workshops are held in academic settings to enable flexible environments that can accommodate both individual working and team working. The flexible environments allow the participants to work in collaboration in wide areas of space that can be organized according to the needs of the clusters. The workshops involve many facilities from scientific experimentation settings to rapid fabrication tools. It can be concluded that the environment and facilities that SG provides need to appeal to specialists from diverse fields who meet for working on interdisciplinary collaborative team-work.

[57] Aish, R., & Woodbury, R. (2005).
[58] Peters, B., & Peters, T. (Eds.). (2013).

3.2. Process Steps of SG Workshops

SG workshops have various process steps that constitute a SG event. The theme of an SG event is decided according to the most contemporary advancements in technology and different disciplines that affect architecture and design. Various workshop proposals are submitted to the committee of SG, and ten of them are selected. Afterward, the workshops are announced, participants make applications, and a limited amount of the participants are selected for the workshops. Then the workshops are conducted in the decided time by the cluster champions, where the participants contribute to the workshops and gain new knowledge. After the four days of workshops, the workshop results are exhibited. The workshops are recorded during the workshops, edited and published on the website of SG after the workshops. Some of the workshops take part in further research and published.

Each SG event focuses on a specific theme that is decided by the SG directors. The theme of SG sets the tone of the ten clusters of that year. The main theme of SG aims to reflect the contemporary advancements in different fields of knowledge that has a potential application for architectural problems. Themes of the SG events illustrate the agenda of computational design. The ten workshop proposals are representatives of the computational design research. In the year 2010, theme of the SG event was "Working Prototypes" which focused on structural exploration by digital fabrication.[59] After that year in SG 2011, the theme was "Building the invisible" that focused on the data-based design and using data in the design processes. The SG 2012 workshop theme was "Material Intensities" that focused on simulation, energy, and environment. In the year 2013, with the SG theme named "Constructing for uncertainty", ambiguity as a concept has been included in the focused design problems.

Starting from 2014, there was an increased tendency on focusing on complex problems of the built environment. In SG 2014, the theme was "Urban Compaction". That year,

[59] SG 2010 challenge: Working Prototypes. (2010). Retrieved March 18, 2019, from https://www.smartgeometry.org/sg2010-barcelona

several problems were defined, such as the densification of the cities and the pollution that they brought with them. The research projects of that year focused on the "implications and opportunities of density for sustainable flows of people, food, energy and waste within building projects and at the planning scale for high rise, high-density cities."[60] The secondary problems were how to design ecological and aesthetic models for living, communication, production, and disposal in dense concentrations. [61] These problems led to research on the infrastructure of the cities and the emergence of the 21st-century megalopolis, by using biomimicry, agent systems, and other computational design models.[62] In SG 2016, the theme was "Hybrid Domains" where a wide range of disciplines from aerospace engineering to chemical crystallography were integrated into the clusters. Finally, the theme of SG 2018 was "Machine Minds". That year, developments in machine learning were seen as an opportunity to contribute to several computational design problems.

The theme of each cluster refers to the main theme of the SG event. Despite being relevant to the theme, the clusters from the same SG event can have distinct research areas. In SG 2018: Machine Minds, the clusters searched for ways to make use of machine learning for different problems. The workshops were present with diverse suggestions that needed different design objectives. For instance, the workshop named "AI strategies for space frame design" focused on structural optimization of trusses by using machine learning.[63] The workshop named "behavioural enviro[NN]ments" focused on how to produce interactive spaces through the observation of mobile agents.[64] The objective of the workshop named "Fresh Eyes" was to generate new design options through teaching an algorithm the existing design products.[65] The three

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[60] SG 2014 challenge: Urban Compaction. (2014). Retrieved March 10, 2019, from https://www.smartgeometry.org/sg2014-hong-kong
[61] Ibid.
[62] Ibid.
[63] AI strategies for space frame design [Video file]. (2018) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2018workshops
[64] behavioural enviro[NN]ments [Video file]. (2018) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2018workshops
[65] Fresh Eyes [Video file]. (2018) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2018workshops

different clusters from SG 2018 indicate that the cluster topics can be various in the same SG event.

In the four days of the workshops, the participants and tutors meet, interact, and work collaboratively for the objective of the cluster. Clusters have background research and previous design suggestions by the cluster champions. The objectives of the clusters can vary from testing a new computational design tool to fabricate a complex structure. According to the objective, some clusters need new design ideas and suggestions through brainstorming and group work. On the other hand, some clusters have a pre-defined agenda where each step is described, and the participants need to work as a team to complete a design objective. This variety points out that the skills needed from the participants also vary, while some clusters focus on individual creativity, some other workshops require compatibility with team-work and collaboration.

After the four days of SG workshops, the outputs are exhibited for sharing the workshop processes with the SG community and participants. In the exhibition, cluster outputs allow the participants to experience and evaluate the design product. For instance, the SG workshop from 2018 named "Data mining the city" involved point clouds that were collected by the workshop participants from the city of Toronto. The point clouds were then merged to simulate the experience of the participants to the other participants with the help of virtual reality (VR).[66] In the exhibition after the four days of the workshop, all the SG 2018 participants had a chance to experience being in the same spots of the city by being immersed by the point clouds which were previously collected by the workshop participants.

[66] Data mining the city [Video file]. (2018) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2018workshops

Figure 3.3. Experiencing “Data Mining the City” during the final exhibition

Sharing design ideas, tools, and methods are essential for inspiring the next generations of designers and design students. Besides, sharing helps synthesize the knowledge and to bring in new innovative research. As research moves incrementally one after another, accessibility of the knowledge by the computational design community is critical. The workshop outcomes are shared with the computational design community after the workshops. Firstly, video recordings of the SG workshops that give clues about the research per cluster are published on the SG website. Secondly, SG workshops share the plugins that are developed by the SG cluster champions for certain design software, such as structural optimization tools *Karamba* and *Kangaroo*, with the computational design community. Lastly, SG workshops can initiate new research opportunities. Some of the SG clusters involve academic projects that can develop after the SG workshops, and publications can be done through the experimentation that is conducted in the SG workshops. For instance, the data from the “Parallel Parametrics” cluster from SG 2016 was included in a research article as a case study for evaluating a developed parametric design system.[67]

[67] Woodbury, R., Mohiuddin, A., Cichy, M., & Mueller, V. (2017). Interactive design galleries: A general approach to interacting with design alternatives. *Design Studies*, *52*, 40-72.

CHAPTER 4

RESEARCH METHODOLOGY

4.1. Qualitative Research Strategy

In this study, computational design learning is investigated through a real-life context: the SG workshops. Also referred to "qualitative inquiry", qualitative research is used when the research problem is complex, and phenomena can only be understood within the duality of the object and subject. [68] In social sciences, qualitative research is used to understand the meaning of human actions that are too complex that quantitative methods may stay inadequate.[69] Qualitative researchers study things in their natural settings, attempting to make sense of or interpret phenomena in terms of the meanings people bring to them.[70]

For this research, SG workshops were investigated through the case study method. A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not evident.[71] Case study research is preferred when the questions "why" and "how" are being posed.[72] While conducting a case study, the investigator has little control over the events.[73] SG workshops were analyzed from multiple data sources, and the topic of computational design learning in the SG workshops was studied and analyzed for this research. The researcher actively participated in the SG

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[68] Schwandt,T.A. (2007). *The Sage Dictionary of Qualitative Inquiry* (3rd ed.). Sage Publications.
[69] Ibid.
[70] Denzin,N.,Lincoln,Y.(1998). *Strategies for Qualitative Inquiry* (3rd ed.). Sage Publications.
[71] Yin, R. K. (2003). *Case Study Research: Design and Methods* (3rd ed., Vol. 5, Applied Social Research Methods Series). Thousand Oaks, California: SAGE Publications.
[72] Ibid.
[73] Ibid.

2018 event to make participant observation and semi-structured interviews with the computational design experts.

4.2. Data Collection

For data collection, textual documents and video archives from the SG website were used. Moreover, the researcher actively participated in the main event of SG in 2018 that was conducted in the University of Toronto, Canada. The workshops were studied before the participation, and re-studied after the participation to SG 2018: Machine Minds, due to the additional data source that semi-structured interviews and participant observations provided. In addition to the case study method, the researcher's active participation to a workshop provided the researcher to experience the learning processes. Using the semi-structured interviews and participant observations, additional knowledge and patterns were included in the findings that were not previously encountered from the written documents or video archives.

4.2.1. Documents about Smartgeometry

The documents that are used for data collection involve the written sources that involve explanations about the objectives, processes, and ideas behind the SG workshops. Because of their overall informative value, documents play an explicit role in any data collection in case studies.[74] The documents that are used in this study are mainly articles that are written by SG directors and workshop tutors. In addition, secondary sources of SG directors, journal articles, and sections from books that are relevant to the SG workshops and the processes that take place in SG were used for this research.

4.2.2. Archival Records

In this study, archival records cover the video-recordings of the previous SG workshops which are archived on its official website. Workshops from the last seven events were recorded as videos of 2-6 minutes per workshop. Video recordings, which

[74] Yin,R.K. (2003)

include visual and audio data were transcribed in order to be used for further data analysis. The records were analyzed iteratively, and qualitative data was produced. The details of the video recordings on the website can be found in Table 1. The video recordings are organized chronologically for each workshop, starting from the first day until the fourth day. In addition to the video recordings, the theme and objectives of each SG event are inscribed on the SG website. Therefore, archival records of the SG workshops, including the video recordings and information from the SG website, play an essential role for data collection from workshops and understanding the concepts of computational design learning in an improved manner.

Table 4.1. *Information about the Workshops per year*

Year	*Event Name*	*Cluster*	*Theme*
2018	Machine Minds	AI strategies for space frame design	Structural Exploration
		Behavioral Environments	Adaptive Space Design
		Data Mining The City	Innovative Visualization
		Fibrous Timber Joints	Structural Exploration
		Fresh Eyes	Machine Learning
		Inside The Black Box	Innovative Visualization
		Materials As Probes	Performative Exploration
		Mind Ex Machina	Robotic Exploration
		Soft Office	Robotic Exploration
		Sound And Signal	Acoustic Exploration
2016	Hybrid Domains	Atmospheric Delight	Data Based Design

2016	Hybrid Domains	Calibrated Modelling Of Form Active Structures	Structural Exploration
		LOGJAM: Polar Orthotropy And Principal Stresses	Material Research
		MARS: Martian Autonomous Robot Swarm	Robotic Exploration
		Mud, Textiles, And Robots For Large Structures	Structural Exploration
		Nano-Gyroids	Structural Exploration
		Parallel Parametrics	Design Generation
		Sensory Detectives	Material Research
		Swarmbot Assemblage	Robotic Exploration
		20.000 Blocks Above The Ground	Design Generation
2014	Urban Compaction	the bearable lightness of being	Structural Exploration
		block	Design Generation
		deep space	Design Generation
		design space exploration for urban compaction	Design Generation
		flows, bits, relationships: visualising social space	Innovative Visualization
		fulldome projections: interfacing ephemeral urbanism	Innovative Visualization

2014	Urban Compaction	HK_smarTowers	Innovative Visualization
		private microclimates	Performative Exploration
		resilient networks	Data-Based Design
		spaces in experience	Innovative Visualization
2013	Constructing for Uncertainty	(A)Synchronous Streams	Data Based Design
		Adaptive Structural Skins	Structural Exploration
		Computer Vision & Freeform Construction	Structural Exploration
		Digital Intuition & Prediction	Design Generation
		Pad	Design Generation
		Projections Of Reality	Data Based Design
		Robotic Foaming	Material Research
		Thermal Reticulations	Performative Exploration
		Transformational Strategies	Data Based Design
		Volatile Territories	Innovative Visualization
2012	Material Intensities: Simulation, Energy, Environment	Beyond Mechanics	Material Research
		Micro Synergetics	Material Research
		Composite Territories	Material Research
		Ceramics 2.0	Material Research
		Material Conflicts	Performative Exploration

2012	Material Intensities: Simulation, Energy, Environment	Transgranular Perspiration	Material Research
		Reactive Acoustic Environments	Acoustic Research
		Form Follows Flow	Data Based Design
		Bioresponsive Building Envelopes	Material Research
		Gridshell Digital Tectonics	Structural Exploration
2011	Building the Invisible	Use The Force	Structural Exploration
		Interacting With The City	Innovative Visualization
		Urban Feeds	Data Based Design
		Cyber Gardens	Robotic Exploration
		Performing Skins	Material Research
		Authored Sensing	Data Based Design
		Agent Construction	Structural Exploration
		Hybrid Space Structures	Structural Exploration
		Reflective Environments	Innovative Visualization
		Responsive Acoustics	Acoustic Exploration
2010	Working Prototypes	Curved Folding	Structural Exploration
		Deep Surfaces	Structural Exploration

2010	Working Prototypes	Design To Destruction	Structural Exploration
		Explicit Bricks	Structural Exploration
		High Tech Design-Low Tech Construction	Structural Exploration
		Inflatable Fabric Envelope	Structural Exploration
		Manufacturing Parametric Acoustic Surfaces	Acoustic Exploration
		Non-Linear Systems Biology & Design	Design Generation
		Parametrics & Physical Interaction	Robotic Exploration
		Snap Fit	Structural Exploration

4.2.3. Participant Observation

Participant observation is the notion of 'being there', of witnessing social action firsthand, and it is a procedure for generating understanding of the ways of life of others.[75] Participant observation needs the researcher to do fieldwork. Fieldwork is defined as;

> "… all those activities that one engages in while in the field including watching, listening, conversing, recording, interpreting, dealing with logistics, facing ethical and political dilemmas, and so on. It is an intensely personal and social press requiring both physical and intellectual stamina, political acumen and moral sensitivity."[76]

In contemporary situations, participant observation has many advantages. Firstly, proximity is provided to the case. Proximity is described as "field-notes are written

[75] Schwandt,T.A. (2007)
[76] Ibid.

contemporaneously with the events, experiences, and interactions they describe and recount."[77] For this study, the researcher participated in the most recent SG event, "SG 2018: Machine Minds" that was held in the Daniels Faculty of Architecture at the University of Toronto in Canada. The processes during the workshop and the conferences were documented by the researcher as field-notes. These notes were reduced and selected according to the relevancy of the question of research.

The researcher took part in the SG event, not only as an observer but also as an active participant, which provided to have first-hand experiences. Throughout the event, observations were recorded on the design processes that take place in the workshops and the SG event. The researcher conducted interviews with computational design experts who take part in the SG workshops. Field notes were taken during the informative presentations about SG, during the workshop explanations locally and the workshop process. Observations were done about the design products, interactions, and the themes. After the field work, activities of participants and the workshop processes were reconstructed through the processes of inscription, transcription, and description in field notes.[78]

The researcher participated in the cluster named "Inside the Black Box" and was engaged in the workshop activities. In the cluster, process steps of the cluster objectives, instructive and experiential learning patterns and relationships between the tutors, participants, tools and the environment were analyzed. Being a participant allowed the researcher to have first-hand experience with the workshop settings. Based on personal communication with the SG directors, champions, and participants, different opinions and experiences were observed and recorded. The researcher experienced the activities that exist in the SG workshop and analyzed why certain activities are done in order to describe and interpret the computational design learning in the SG workshops.

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[77] Atkinson, P., Coffey, A., Delamont, S., Lofland, J., & Lofland, L. (Eds.). (2007). *Handbook of Ethnography*. Sage Publications.
[78] Schwandt,T.A. (2007)

Inside the Black Box cluster was formed by two cluster champions, four experts, and eight cluster participants. Four of the participants were post-graduate students. Three participants were from practice, involving architecture offices from different countries. One participant was an associate professor. A similar distribution of participants from academia and practice was observed in the other SG 2018 workshops.

The research question specific to the participated workshop “Inside the Black Box” was “How can the design solutions be visualized in a three-dimensional immersive design matrix that involves various design criteria?” The objective of this workshop is visualizing design outputs relatively to each other by using a 3D environment through virtual reality (VR). Each participant was asked to design a tower with ten parametric variations in Toronto that are evaluated according to the weather data. Specific software tools were designed and scripted by the tutors, who are architects and computer scientists, in order to provide the required digital visualization medium. During the workshop phase, towers were modeled by the participants using a visual parametric software tool. Afterward, the models were assembled in an interoperable software to make a comparison by performance criteria. Then the models were exported to the visualization software in a 3D matrix and finally exported to the VR software. The towers were also 3D printed, and a physical model of the data topology was produced.

Figure 4.1. Final exhibition of "Inside the Black Box" (Öykü Acıcan)

4.2.4. Interviews

One of the most important sources of a case study is the interviews.[79] For this research, the researcher conducted semi-structured interviews with ten computational design experts that are involved in SG as directors and cluster champions during the SG event that was participated. In the semi-structured interviews, the key respondents were asked about the computational design processes, interdisciplinarity, innovation, and the relationship between these elements. The interview questions were decided considering the semi-structured and flexible nature of the case study interviews. The responses from the interviews were audio-recorded, transcribed, and coded. The questions aimed to understand the important factors behind the computational design processes in the SG workshops, such as interdisciplinarity and innovation. In this research, the observations and the participant responses were interpreted within the framework of the computational design. Information on the interviewees and their experience in the related fields can be found in Table 2. The questions that were directed are as follows;

[79] Yin,R.K. (2003)

1. To what extent does interdisciplinarity have an influence on the SG workshops?

2. What is the relationship between interdisciplinarity and innovation in SG?

3. What are the potentials and impacts of the SG innovation on architecture?

4. What can be an example of an innovation that SG has brought in?

5. What are the critical concepts that are most important for an SG workshop?

4.3. Data Analysis

For the data analysis, interviews were transcribed. The transcribed interviews and the field notes were coded. The coding was used for interpretations and the themes were derived from the codes. Data was analyzed in an interpretive manner, using data reduction by "focusing, simplifying, abstracting and transforming "raw" data."[80] The data reduction enabled to analyze certain concepts deeper within the data. Afterward, patterns and regularities were identified, and that produced the main themes of the findings. Decision of the patterns and themes resulted in conclusion drawing.[81] For the coding, the meanings were used to derive themes instead of words or word counts, because the interviewees use different words and sentences that can stand for the same meaning. Therefore, the choice of the themes was identified by the researcher where the different words "embedded in a particular logic or conceptual lens".[82]

The analyzed data from the documents, archival records, interviews, and participant observations were evaluated with a computational design learning perspective. From the written documents about SG and archival video recordings in the SG website, a general scheme of concepts was determined. During the participation, new concepts and observations that were not initially considered were integrated into the scheme. After the data analysis, important aspects of computational design learning in SG were

[80] Silverman, D. (2013). Doing qualitative research: A practical handbook. SAGE publications limited.
[81] Ibid.
[82] Miles, M. B., Huberman, A. M., Huberman, M. A., & Huberman, M. (1994). Qualitative data analysis: An expanded sourcebook. sage.

identified by categories and sub-categories. The data from the archival records and written sources constituted a framework which was discussed in Chapter 3: “The Case: Smartgeometry”. The participant data were analyzed together with the previous data to be explained under Chapter 5: Findings.

Table 4.2. *Information about the Interviewees*

Code	*Role*	*Specialization*	*Experience (Years)*	*Duration of the Interview(mins)*
Interviewee 1	SG Director	Visual Analytics	38	15.14
Interviewee 2	SG Director	Mathematics in Computational Design	30	19.39
Interviewee 3	Cluster Champion	Computational Design	10	09.46
Interviewee 4	Cluster Champion	Robotics	10	14.25
Interviewee 5	Cluster Champion	Performative Design	17	05.45
Interviewee 6	Cluster Champion	Computational Design	19	10.53
Interviewee 7	Cluster Champion	Cybernetics	10	09.40
Interviewee 8	Cluster Champion	Machine Learning	10	08.58
Interviewee 9	Cluster Champion	Interaction Design	26	13.36
Interviewee 10	Cluster Champion	Computational Design	15	60.01

CHAPTER 5

FINDINGS ON COMPUTATIONAL DESIGN LEARNING IN SG

Contemporary SG workshops present experiential learning environments to a diverse range of participants from academia and practice. It was found out that, the keyword *learning* is of critical importance considering the interviews. In addition, being a participant enabled the researcher to experience the learning process by herself. After the data analyses, some key concepts were identified that are significant for computational design learning. Some key findings as a result of multiple resources, are presented in this chapter. These findings include the key role of *research* in design processes, *interdisciplinary collaboration*, the critical role of *computational design tools, democratization*, *customization, rapidness,* and *interactiveness*.

5.1. The Integration of Research and Learning in SG

The first and basic finding from the multiple data sources is that design and research are inseparable in SG. SG workshops enable experimenting and learning through digital and physical artifact creation processes. It was concluded from the data analyses that research has a vital role in the design process. Two types of research were observed in the SG workshops, which are *research for design* and *research through design*. While *research for design* is defined as the investigation of knowledge that include but are not limited to materials, mechanics and function that informs the design; *research through design* is defined as "The designing act of creating prototypes is in itself a potential generator of knowledge (if only its insights do not disappear into the prototype, but are fed back into the disciplinary and cross-disciplinary platforms that can fit these insights into the growth of theory)."[83]

Research for design is used both before the workshops and during the workshops. Firstly, interviewees underline the importance of background research for each

[83] Stappers, P. J. (2007).

workshop. Background research involves the integration of research from different disciplines about the tools, methods, and processes for certain goals. For instance, the aim of the SG 2018 workshop named “behavioral enviroNNments” was to design an adaptive environment whose form changes according to the movements of the inhabitants. A modular setting was designed, and a machine learning algorithm was developed to design a flexible environment that is sensitive to movement. Ants were placed in the designed setting to provide movement data, and various sensors tracked the movements of the ants. The decision of using ants stems from the research of one of the cluster champions, Kate Jefferey, who is specialized in behavioral neuroscience. Jefferey states that her research involves working with various animals such as rats and mice, but it is the ants that can generate enough data to feed the machine learning algorithm in the short duration of workshops.[84] Similarly, background research on machine learning was required to develop a new machine learning algorithm that can track the paths of the ants and extract commonalities. The integration of the different background research enables this cluster to plan the tools, method and the process.

Research for design is also an inseparable phase during the SG workshops. The cluster champions provide various tools for data collection during the workshops. Afterward, the collected data can either inform the design output or be visualized. For example, the aim of the SG 2013 workshop named “(a)synchronous streams” was to develop a novel system for urban site analysis and visualization. Research about the site was required to produce the intended visualization. For that objective, helium balloons and sensors were used to collect multiple data from the environment, and afterward, the collected data was represented visually. The knowledge gathered during the workshop was then used for the production of a final output.

The second type of research that is practiced in some of the SG workshops is *research through design*. Research through design is conducted in some of the SG workshops by the cluster champions, and participants become involved in the research process.

[84] behavioral enviro[NN]ments [Video file]. (2018)

According to interviewee 2, the SG workshops and their outputs can be used for further research such as the SG 2013 workshop named "thermal reticulations", which became the subject of the research article named "Understanding Heat Transfer Performance for Designing Better Façades". In the stated workshop, participants designed individual façade elements, which were placed into a system for the measurement of thermal behavior. This process was a research on the "design of building façades to mediate external and internal thermal conditions" that used empirical measurement with a controlled experiment.[85] The experimentation phase was conducted during the SG 2013 workshop, and the results of the research was published as a research article in ACADIA 2013 as a knowledge contribution to the field. Another example for research through design in SG can be given from the SG 2016 workshop named "parallel parametrics", which took part in the evaluation section of the research article named "Interactive design galleries: A general approach to interacting with design alternatives" that was published in the journal "Design Studies".[86]

Key figures have discussed the impacts of research in learning. According to Frayling, research is the most critical nutrient of learning.[87] Interviewees emphasize the positive effects of learning through research. According to interviewee 2, the research behind the workshop proposals and the requirement of producing a new outcome support the learning in SG. The participants gain new knowledge by developing artifacts or experimenting with the tools that are provided by the cluster champions. According to interviewee 8, SG is a laboratory for exposing novel research problems with a small audience and experimenting collaboratively without knowing the outcome in advance. For instance, the SG 2018 workshop named "fibrous timber joints" is originally a research project conducted by a collaborative team of researchers and practitioners.

[85] Burry, J., Salim, F., Williams, M., Anton Nielsen, S., Pena de Leon, A., Sharaidin, K., & Burry, M. (2013). Understanding heat transfer performance for designing better facades. In *Proc. ACADIA* (Vol. 13, pp. 71-78).
[86] Woodbury, R., Mohiuddin, A., Cichy, M., & Mueller, V. (2017).
[87] Frayling, C. (1994). Research in art and design (Royal College of Art Research Papers, vol 1, no 1, 1993/4.

The physical construction of the project was achieved for the first time during the SG 2018 workshop. Participants actively took part in the construction process and learned about the newly proposed technique of producing structures with carbon fiber joints.

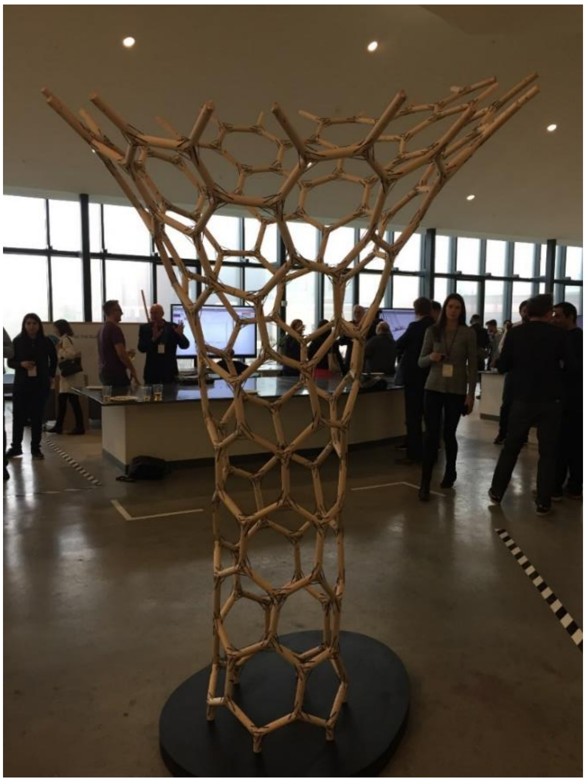

Figure 5.1. Final product of the cluster "Fibrous Timber Joints" (Öykü Acıcan)

Experimentation with certain tools that are provided by the cluster champions is the main focus of some SG workshops. Participants learn about specific concepts or methods during the experimentations. The focus of the experimental research is usually on the process, and a final product is usually not planned. For instance, the SG 2016 workshop named "swarmbot assemblage" is a research that aims to experiment on the concept *stigmergy,* which means the complex behaviors in nature formed by collective embodied intelligence, such as the ant colonies. The stated workshop aims to conduct research on complexity and emergence by the collective movements of simple units using simple robots, which produces embodied programming. Simple robots were placed in a setting in order to mimic the stigmergic behavior of ants, while small geometric objects were placed and moved by the simple robots. After collective behavior of the robots, swarms of geometric shapes emerged. "Swarmbot assemblage" is a workshop where a final product was not planned, but the process was observed and experimented.

> Finding 1. Research and design are inseparable in the SG workshops. Research in SG is achieved through the active development of design artifacts or experimentation with computational design tools.

5.2. The Significance of Interdisciplinary Collaboration

Interdisciplinary collaboration has been identified as one of the most significant factors in computational design education and SG. Klein and Newell describe interdisciplinarity as "a process of integrating insights of different disciplinary perspectives through the construction of a more comprehensive perspective for answering a question, solving a problem or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession."[88] As opposed to multi-disciplinarity, which is the adjoining of multiple disciplines in one context, interdisciplinarity provides the integration and synthesis of different areas of knowledge that produces new perspectives.[89]

The complexity of design problems and interdisciplinarity have co-evolved in SG, together affecting the workshop proposals that exist in the agenda of SG. An example is the shift in focus from early SG attempts in form-finding and paneling exercises towards a multiplicity of subjects that include but are not limited to machine learning, material explorations, performative design approaches, or design tool integration at various scales. According to Mark Burry, the definition of "smart" from the name of SG is not used for creating complex geometries anymore but is used for integrating

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[88] Klein, J. T., & Newell, W. H. (1997). Advancing interdisciplinary studies. *Handbook of the undergraduate curriculum: A comprehensive guide to purposes, structures, practices, and change*, 393-415.

[89] Self, J. A., & Baek, J. S. (2016). Interdisciplinarity in design education: Understanding the undergraduate student experience. *International Journal of Technology and Design Education*. doi:10.1007/s10798-016-9355-2

knowledge from various disciplines such as architecture, mathematics, and engineering. [90] This idea of interdisciplinarity can be observed in every SG event. According to interviewee 3, the main research question of the year 2018 is "how the design disciplines are going to interact and collaborate with the cutting edge research in computer science and machine learning?"

The participants and tutors in SG were defined as "Researcher-practitioners of design from architecture, engineering, industrial design, mathematics, natural sciences, and the arts, and other cross disciplinarians from beyond; and students, practitioners, educators, or any combination thereof."[91] Diversity in the disciplines of contributors to SG provide an inclusive platform where learning from each other is inevitable. Interviewees agree on the positive effects of diversity in SG to learn computational design. Interviewee 7 states that the interdisciplinary nature of SG promotes learning further due to the interaction between the cluster champions and participants who have different areas of interests. Participants and tutors of SG learn more by sharing the individual skills and knowledge. Interviewee 7 exemplifies that the complex research problem of the workshop that he conducts requires different fields of knowledge such as cybernetics and object tracking to be used together, and that is achieved by the presence of different specialists whose knowledge are shared in between.

According to interviewee 10, ideation beyond the usual and habitual takes place when participants from different disciplines come together and produce new knowledge by the collective research processes. Ideation is defined as the process of "generating, developing, and communicating ideas, where an idea is understood as a basic element of thought that can be either visual, concrete, or abstract."[92] Innovative ideation happens in interdisciplinary collaboration because different disciplines uncover the limits and misconceptions of each other. Interviewee 10 stresses that an idea that has

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[90] Burry, M. (2013). From Descriptive Geometry to Smartgeometry: First Steps towards Digital Architecture. In B. Peters & T. Peters (Eds.)
[91] Mueller, V., & Smith, M. (2013).
[92] Jonson, B. (2005). Design ideation: the conceptual sketch in the digital age. *Design studies*, *26*(6), 613-624.

not been thought or understood in one discipline might act as an indicator with the involvement of a different discipline to the same task. According to the same interviewee, in SG, the gathering of participants and tutors from different educational backgrounds that have different perspectives, ways of thinking and processes of developing methodologies make them un-learn their existing knowledge and start learning from each other. In this manner, an interdisciplinary study is not a simple supplement but is complementary to and corrective of the disciplines.[93]

Interdisciplinary collaboration is not only effective in learning tangible knowledge from different fields but also critical in intangible cognitive aspects that are needed for knowledge-making. Firstly, interdisciplinary collaboration is widely associated with creativity. According to Sutton et al., "the heterogeneous sets of skills and experiences of members of interdisciplinary teams give rise to an enhanced capacity for creativity, innovation, and novelty."[94] Moreover, according to Nicoll et al., "complex design tasks call for the integration of knowledge from different disciplines."[95] Interviewee 4 stresses that although SG is an architectural event, workshops work on complex problems beyond the limits of architecture where interdisciplinary knowledge brings in creative opportunities. Secondly, interdisciplinarity was observed to avoid design fixation during the SG workshops. Design fixation was defined as the "blind adherence to a set of ideas or concepts limiting the output of conceptual design." [96] Thomas et al. argue that design fixation is a barrier that constrains the exploration of the design space due to the designers' tendency of applying previous design ideas. [97]According to Goldschmidt, "stimuli from different domains during a design process can avoid design fixation."[98] As

[93] Klein, J. T., & Newell, W. H. (1997)
[94] Sutton, R. I., & Hargadon, A. B. (1996). Brainstorming groups in context: Effectiveness in a product design firm. *Administrative Science Quarterly*, 41, 685-718).
[95] Nicol, D., & Pilling, S. (2000).
[96] Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design studies*, *12*(1), 3-11.
[97] Thomas, J., & Strickfaden, M. (2018). From Industrial Design Education to Practice: Creating Discipline Through Design Sprints (W. Chung & C. S. Shin, Eds.). In *Advances in Interdisciplinary Practice in Industrial Design* (Vol. 790, pp. 111-121). Springer.
[98] Goldschmidt, G. (2011). Avoiding design fixation: transformation and abstraction in mapping from source to target. *The Journal of creative behavior*, *45*(2), 92-100.

previously explained, concepts such as "ideation beyond usual and habitual" and "un-learning" also help to avoid design fixation during the SG workshops.

In SG, subjects that are not considered as part of the architectural domain can interact and form research proposals. For instance, the workshop named *Nano-Gyroids* investigates whether atomic gyroid-formations can contribute to the design of *transformative* –flexible- objects and spaces.[99] Gyroid-formations are analyzed by crystallography, which is a sub-discipline of chemistry in the atomic scale. Although crystallography and architecture may seem unrelated, the potentials of crystallography on producing architectural forms were explored through this workshop. During the workshop, experts in crystallography provided insights about the formations of the atomic gyroid-forms. The participants interpreted the gyroid forms by using various plug-ins and software. Afterward, participants physically produced the digital models by using various materials. The capability of the atomic gyroid forms to change shape was interpreted on a larger scale that brought in the emergence of flexible objects that are capable of transforming and changing shape. This workshop synthesizes very distinct fields of knowledge that enables the ideation of a new method of production of flexible and transformative objects.

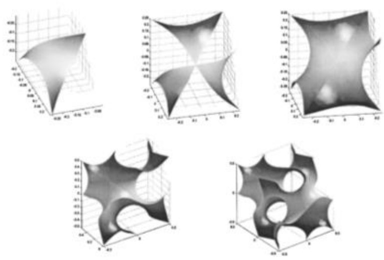

Figure 5.2. Gyroid Formations in Crystallography[100]

[99] Nano-gyroids [Video file]. (2016) Retrieved December 18, 2018 from https://www.smartgeometry.org/sg2016workshops
[100] Enlow, J. D., Enlow, R. L., McGrath, K. M., & Tate, M. W. (2004). Modeling liquid crystal bilayer structures with minimal surfaces. *The Journal of Chemical Physics, 120*(4), 1981-1989.

Figure 5.3. Mimicking the gyroid formations in SG[101]

> Finding 2. Interdisciplinary collaboration can accelerate the learning process by rapid and timely sharing of knowledge, the recognition of the limits of a single discipline, and approaching a problem from different perspectives.

5.2.1. Communication and Overcoming the Disciplinary Language Barriers

SG workshops involve interdisciplinary groups that work collaboratively. As the collaboration in SG needs to be interdisciplinary, communication is very significant. In literature, it is widely argued that collaboration is closely related to collective creativity and an increased need for communication. Sanders defines collective creativity as "the combination of disparate ideas shared by two or more people." According to Sanders, "collective creativity can be a powerful tool and more culturally relevant to a given situation than individual creativity as seen with effective collaboration through teamwork."[102] In SG, different levels of collaboration takes place. The cluster champions collaborate in the development of a design proposal before the workshops. During the workshops, the workshop participants and the champions communicate and collaborate to share knowledge and learn from each other. Even after the workshops, the workshop results are communicated with the wider audience through books, publications, and websites.

[101] Nano-gyroids [Video file]. (2016)
[102] Sanders, L. (2001). Collective Creativity. *LOOP: AIGA Journal of Interaction Design Education*. Retrieved from http://echo.iat.sfu.ca/library/sanders_01_collective_creativity.pdf

During the case studies, the language problem was widely argued as a result of interdisciplinarity collaboration by the Interviewees 2, 3, 6, 8, 10. Participants and champions in SG have different backgrounds in education and practice, which causes different ways of approaching problems and solutions. Disciplinary knowledge is usually considered as hard to share or communicate. As the terminologies are different among disciplines, it is common to use the same words that have different meanings, which causes disagreements and difficulties. According to interviewee 2, although the SG workshops appear to concentrate on integrating the technological advancements to architecture, integrating the different disciplinary languages is more critical for SG. According to interviewee 3, the challenge of communication between an architect with another specialist depends on the gap between the disciplines, and when the gap is larger, it takes more time to develop and share understanding. It was observed that several methods are applied in SG workshops in order to overcome disciplinary language problems.

The first and the most common way of communication is the use of natural language. However, when a complex topic is on the focus, disciplinary languages need to become involved. Interdisciplinary teams involve specialists with different educational foundations that have specific disciplinary languages and terminologies. The very same word may have different meanings in different terminologies. This condition has the risk of creating conflicts and misunderstandings between the team members, and the communication may become difficult. Interviewees 2 and 3 state that depending on the gap between the disciplines, a shared understanding is required for communicating during a collaborative design process. According to interviewee 2, a metaphorical language can be used in order to facilitate interdisciplinary communication. A simple terminology that involves the basic concepts from each discipline can be developed. However, an interdisciplinary terminology carries the risk of remaining superficial. Moreover, it is still not guaranteed to overcome the conflicts caused by the use of verbal language.

The second method of overcoming the disciplinary language problem and providing a shared language is to use a visual language. According to interviewee 3, producing visualizations accelerate the communication problem in complex interdisciplinary projects where the researchers tend to think in their disciplinary language. It is assumed by the interviewees that visual language is more perceptible than verbal language and therefore may create less conflict by uniting the team members around the same visual representation that words may not be enough to explain. However, visual language is an abstraction that is open to interpretation. In the same manner with terminologies, different disciplines involve different modes of visual representation. When the level of abstraction increases, it becomes harder to understand the represented object and the information that representation involves. Similarly, according to Goldschmidt, specialists can learn the representational language of the disciplines that they are interacting with, otherwise, it may be hard to understand each other's representations.[103]

The disciplinary language problem can alternatively be overcome through technologies of interoperability. According to the interviewees, a solution for accelerating communication is to assemble the different perspectives of the workshop contributors through interoperability, by placing a data interpreter at the center that allows to understand and communicate between different disciplinary models that encapsulate the disciplinary knowledge. Interoperability was defined as the "process of streamlining information exchange between two or more model authoring platforms".[104] As interoperability is a preferred method for rapid interdisciplinary projects, interviewees agree on the importance of interoperability for the SG workshops. Interoperability enables the team members to work with the same core model in different platforms. However, instead of bringing the individuals together, interoperability enables the individuals to work separately by placing a translator in-

[103] Goldschmidt, G. (2019, July 10). *Disciplinary Knowledge and the Design Space*. Speech presented at "DRS Learn X Design 2019" Fifth International Conference for Design Education Researchers in Middle East Technical University, Ankara.
[104] Deutsch, R. (2017).

between. It can be commented that interoperability can provide an indirect communication between the individuals from different disciplines through the tools, but it may not be enough to overcome the language barriers.

5.2.2. The Role of Architects

The role of architects within interdisciplinary groups was placed into focus during the study. In interdisciplinary design settings, architects can have various roles relative to the other disciplines. Architects may be the leaders or the participants of an interdisciplinary team in the design process. On the other hand, in an interdisciplinary setting, according to interviewee 2, architects may run the risk of remaining subordinate to other domains. According to the same interviewee, in such situations, interdisciplinary thinking and the ability of coordination are essential skills that the architects must have in order to be an active member of an interdisciplinary team.

The focus of the SG workshops is on how to apply new knowledge from different fields into architecture, rather than discussing the existing architectural knowledge. Interviewees agree on the fact that architecture is an interdisciplinary practice. There are no limits of architectural knowledge, as architecture adopts knowledge from different domains. To actively participate and even to lead a design process, interviewees agree that architects need to be able to engage in phenomena that are not necessarily present in the domain of architecture, such as robotics or material science. In order to engage with phenomena from different domains, architects have significant responsibilities, such as communicating with specialists from different disciplines. According to interviewees 2 and 4, the first duty of architects, therefore, is to be aware that the specialists from different fields have different mindsets and perspectives.

Interviewee 10 states that comfort zone is formed when the disciplinary knowledge sustains the architect. Different domains of knowledge set a barrier to architectural knowledge, and that can help the architects to escape from the comfort zone. In this condition, architects can play a significant role in the interdisciplinary settings if they adjust themselves according to the disciplinary barriers, instead of changing direction to avoid the barriers. Interviewee 10 underlines that being out of the comfort zone and being open to new design challenges and experimentations is a triggering force for creativity. Architects can avoid the comfort zone by being aware of the fact that architectural knowledge may not be enough to solve complex design problems, and by changing the methods and the ways of asking questions to different problems. According to interviewee 10, although the short duration of the SG workshops may not provide sufficient learning of a certain computational design tool or method, participants recognize in the SG environment that their knowledge is limited to a single disciplinary framework. Learning about the limitations of a single discipline is a valuable insight in order to gain the skills to be open-minded and progressive.

The knowledge and skills that an architect must have to practice computational design is expanding over the years. Interviewees agree that the know-how about computational design has been increasing and aggregating. According to Oxman, "computational design is becoming more demanding regarding the knowledge of computational design and scripting tools for the new generation."[105] According to interviewees 1 and 4, cutting edge technology of the past has become the mainstream now. For instance, it is ordinary to see complex geometries in buildings, or the presence of digital fabrication facilities in architectural design studios. Similarly, Oxman states that many of the new research processes and subjects such as acquiring knowledge of architectural geometry and digital enabling skills are already part of the agenda of the leading architecture schools.[106]

Interviewee 2 advocates that architects need to be aware of the "affordances of other industries" in architecture. The word "affordance" was initially coined by the perceptual psychologist J. J. Gibson (1977, 1979) to refer to the actionable properties between the world and an actor (a person or animal).[107] It was explained that affordances of artifacts determine "how the artifacts can be used" and that designers

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[105] Oxman, R. (2006) Theory and design in the first digital age, *Design Studies*, 27:3**;** 229-65.
[106] Oxman, R., Oxman, R. (2010).
[107] Norman, D. A. (1999). Affordance, conventions, and design. *interactions*, *6*(3), 38-43.

create the affordances of artifacts.[108] For SG, affordances are based on the relationships between the knowledge from architecture and the other disciplines. In the case of SG, architects determine how a design tool and method of a different discipline can be applied to the field of architecture. During the early years of SG, when the aim was to create complex geometries, industrial design software that is used for designing aircraft and ships were adopted and used for creating complex architectural geometry. In this case, according to the interviewees 2 and 9, architects in SG benefited from the affordances of software that is initially designed for a different domain than architecture The relationship between the artifact (a tool or method) and the actor (designer) is very subjective, ad-hoc, utilitarian, and interpretative. It also requires creativity.

There are conflicting comments about the impacts of expanding the limits of architecture by being open to different tools and methods. Interviewees 2, 4, and 9 state that a paradigm shift has been realized within the integration of new computational tools and methods to architectural design process. According to the same interviewees, the involvement of the programming environment and rapid experimentation in architectural design processes are some of the evidence that proves the paradigm shift. Besides, the incremental integration of new technologies to the mainstream of architectural production may indicate an ongoing innovation in the field. However, the rest of the interviewees do not agree that a paradigm shift happened. Despite the literature on a paradigm shift, some of the real practitioners do not see a major change in the built environment due to the advancement of computational design in architecture. Interviewees 6 and 8 express that architects can examine various details now due to the new technologies, but the overall paradigm of architecture has not changed. Interviewee 10 states that the duration of SG is very short for producing a significant impact. For creating a substantial outcome that might bring a more considerable impact, more time is needed than the four days of the

[108] Maier, J. R., & Fadel, G. M. (2009). Affordance based design: a relational theory for design. *Research in Engineering Design*, *20*(1), 13-27.

workshops. The interviewees advocate that with the integration of technology and computational design, architects can experiment on particular objectives, learn to work collaboratively and share knowledge, but that does not have to indicate a paradigm shift.

> Finding 3. Awareness of the "affordances of other industries" is one of the main drivers behind the creativity and innovativeness of computational design.

5.3. The Critical Role of Tools for Computational Design Learning

Findings from the interviews support that tools and tool-making is very critical for the SG workshops and the SG community. In SG, computational design tools for generating, visualizing, optimizing, sensing, and materializing play a critical role for design research, interdisciplinary working, and experiential learning. Participants in SG learn various uses of computational design tools during the workshops. The tools explored and developed in SG vary concerning the theme of the workshop. A wide range of topics have been covered, from structural form-finding (i.e. gridshell structures, agent-based structural design, design with physics engines, adaptive structural skins, form-active structures), material experimentation (composites, ceramics, bricks), parametric design optimization, data-informed design strategies (i.e. acoustical, urban, thermal, humidity data), data/form visualization, robotic fabrication/assembly, machine learning methods, and computer vision.

Developing computational design tools have a considerable part in discovery and experimentation that take place in the SG workshops. According to interviewee 2, computational design tools and the development of further tools are encouraged in SG because the tools enable new potentials for exploring design in new ways. Similarly, interviewee 9 advocates that building the right tools is the first step for discoveries. As previously stated, new computational design tools are developed in SG with the *affordances* of different disciplines. According to interviewee 5, in the SG workshops, synergies are formed between the techniques, methods, and materials of different disciplines. It is the cluster champions who develop new tools for the participants.

Developing tools can take place either during the background research or during the workshops. Participants gain knowledge through the usage of the developed and customized tools that make discovery and experimentation possible. For instance, the cluster named "soft office" involved customized robots that can weave vertical partition structures. The cluster champion Maria Yoblanina previously developed multiple robots that can weave coordinately.[109] Cluster participants learned how to use the weaving robots by experimenting and discovering the capabilities of multiple robots for producing weaved structures from carbon fiber.

Figure 5.4. "Soft Office" cluster. (Öykü Acıcan)

According to Belland, in education, scaffolding is the assistance or guidance provided by parents or teachers that aim to extend students' current knowledge and skills towards independent problem-solving.[110] Scaffolding during learning requires that the instructors offer the students temporary support, increasing the students' skill acquisition and comprehension that are essential to complete specific tasks. The high level of tool competency necessary for computational design calls for certain degrees of instructional support. This support is gradually eliminated by time, as the student

[109] Yablonina, M., Prado, M., Baharlou, E., Schwinn, T., & Menges, A. (2017). Mobile Robotic Fabrication System for Filament Structures. In A. Menges, B. Sheil, R. Glynn, & M. Skavara (Eds.), *Fabricate: Rethinking Design and Construction* (pp. 202–209). London: UCL Press.
[110] Belland, B.R. (2017).

feels competent and ready to take the responsibility to complete creative design tasks independently. SG workshops, similarly, invest in both instructional learning through explicit guidance for tool-using and exploratory learning by allowing the participants to apply their computational skills and knowledge on creative design problems, further enhancing learning-by-doing.

The integration of sensing tools in the computational design processes can help the participants to learn about many aspects through the responsive design processes and outcomes. According to the interviewee 10, sensing tools such as thermal cameras, heat sensors, light sensors and tracking tools for data collection have become more accessible, and are increasingly being used by the SG workshops. Interviewee 2 states that the dominant agenda of SG during its early years was to manipulate geometry. Whereas, a critical shift of focus took place recently, which involved the integration of environmental data, such as air, light, sound, atmosphere, humidity, the behavior of inhabitants, and urban flows. Integration of environmental data into the design process can be used for producing interactive design outputs that are responsive to the changes in environmental forces or user behavior. Interviewees agree that clusters that make use of the sensing tools enable the participants to be informed by their surroundings, gain environmental awareness and learn different ways in which the collected data can be integrated into the design processes. For instance, the output of the SG 2016 cluster named “sensory detectives” was a modular responsive pavilion whose color changes according to the dynamics of heat, moisture, and air, with the use of multiple electronic sensors.[111] One of the participants of the stated workshop states that the participants became more aware of the environmental aspects that can have a significant impact on the design process.[112]

Materialization tools that are used in the SG workshops are observed to provide learning-by-doing that may have positive effects on computational design learning.

[111] Sensory Detectives [Video file]. (2016) Retrieved December 30, 2018 from https://www.smartgeometry.org/sg2016workshops
[112] Ibid.

The tools for materializing in SG are usually technologies adapted from the industry, that enable digital fabrication, rapid prototyping, and many customized methods of materialization. Due to the use of various tools such as CNC machines, 3D printers, and robots to produce complex forms, participants can experiment on new materialization methods. Besides, participants can grasp complex concepts of computational design with the experiential knowledge that is gained during the materialization processes. According to Blikstein, the use of materialization tools and physically "making" supports experiential and constructive learning. [113] For instance, the SG 2013 workshop named "Robotic Foaming" is an experimental workshop where robots are used for a specific method of fabrication by pulling a filamentous foam material that becomes stable after drying. During the workshop, participants could experiment with the production method and learned about the self-supporting structures by materialization. Participants could learn about the behavior of the specific foam material with active experimentation by using the robots. The cluster champion Kadri Temre states that after the four days of the workshop, some of the participants could master the material properties and produced successful and stable structures from the used material.[114]

[113] Blikstein, P. (2013). Digital fabrication and 'making'in education: The democratization of invention. *FabLabs: Of Machines, Makers and Inventors, 4*, 1-21.
[114] Robotic Foaming [Video file]. (2013). Retrieved December 25, 2018 from https://www.smartgeometry.org/sg2013workshops

Figure 5.5. Materialization of the tower designs from “Inside the Black Box” (Öykü Acıcan).

Finding 4. Computational design involves a cycle between the digital and the physical. This cycle of generation and materialization of design contributes to the computational design learning. In this process, instruction of the computational design tools can establish a scaffolding for the participants and the exploration afterward can complement the instructive process.

5.4. The importance of Democratization for Collective Learning

SG is an environment where interdisciplinary groups are required to solve complex design problems creatively. For that reason, a collaboration between the workshop contributors and accessibility to the facilities are crucial. Equality between the participants and their accessibility to other participants, tutors, and tools are important factors for the SG workshops. According to Potts, equality enables respect to others and the confidence to contribute to the group work.[115] Interviewees agree on the fact that in SG, an environment based on respect and confidence can be achieved because the participants and tutors are considered as equals.

[115] Potts,W. (2000). The Design Studio as a Vehicle to Change: The Portsmouth Model. In S. Pilling (Ed.), *Changing Architectural Education : Towards a new Professionalism* (pp. 208-216). London: RIBA Publications.

In the context of higher education, it is argued that the misdistribution of power between students and professors should be balanced in order to democratize the studio, which can encourage students to take on the primary responsibility.[116] SG workshops offer equal opportunity to its participants to contribute to the group work without a social or disciplinary hierarchy, and that improves communication. During the event, it was observed that the collaborative champion-participant relationship of the SG workshops has less hierarchy than the professor-student relationship of a design studio. In an environment as SG provides, cluster champions and participants learn equally from each other.

Figure 5.6. "Inside the Black Box" Cluster participants and tutors working together (Öykü Acıcan)

Interviewees concur that the computational design tools have had a significant impact on engaging a community of computational designers. Networking has gained importance because the participants realize during SG workshops that other participants have different skillsets, and by sharing the skills, reciprocal learning can happen rapidly. Due to the increased importance placed upon sharing and networking, computational design tools have become more accessible. Interviewee 8 states that the

[116] Dutton, T. A. (1987). Design and Studio Pedagogy. *Journal of Architectural Education, 41*(1), 16-25.

SG community created an environment where everybody is at the same level, and everybody can share the tools and information.

The democratized environment of SG allows having collaboration not only inside the workshops but also between the workshops. For instance, the workshop named "Parallel Parametrics" from the SG 2016 event aims to test software that enables to visualize and coordinate between different alternatives and permutations of a parametrically designed object. The software makes it possible to borrow elements from different design alternatives of the same design script to reach the final design decision rapidly. Workshop champion Mark Cichy states that participants from other clusters, who had problems in optimizing their design outputs, cross collaborated with the Parallel Parametrics cluster and used the stated software in order to utilize and coordinate their designs.[117] Sharing the tools and knowledge that is produced in one cluster with the other clusters indicate that sharing knowledge is prevalent even during the workshops.

The physical environment where the SG events take place is of critical importance to provide democratization. SG started to organize its events in design schools since 2010, starting with the Institute for Advanced Architecture of Catalonia (IAAC). Beforehand, SG events used to take place in hotels, which are effective for conferences but not effective for collaborative working and experimentation. According to interviewee 10, after switching the location from hotels to design schools, SG workshops changed their mode from working on individual problems into non-hierarchic collaborative research projects. SG 2018 was held in the University of Toronto, Daniels Faculty of Architecture. The studio space that is provided is an open area that can host many facilities and equipment. The open area also enables diverse activities for a large amount of participants. The open plan layout of the physical environment within which SG 2018 took place points to the importance of interaction between different workshops. It was observed that it is encouraged for the participants

[117] Parallel Parametrics [Video file]. (2016) Retrieved December 24, 2018 from https://www.smartgeometry.org/sg2016workshops

to visit all the workshops and be informed about other simultaneous research processes. The increase in the interactions helps the formation of a community.

Figure 5.7. SG 2018 Toronto, in Daniels Faculty of Architecture (Öykü Acıcan)

Figure 5.8. SG 2018 Toronto, in Daniels Faculty of Architecture (Öykü Acıcan)

With the SG community, learning extends beyond the limits of the classroom towards a network of designers, architects, and other specialists exchanging knowledge and sharing their ideas and code. The interviewees concur that the creation of a community and democratization of the new computational tools is one of the most significant impacts that SG has brought to the computational design field. Interviewees state that the open source movement in the SG community made knowledge transfer and translation much faster, and that has positive effects on both mutual learning and equality. As knowledge becomes more accessible, everyone can learn from each other, which increases the pace of learning collectively.

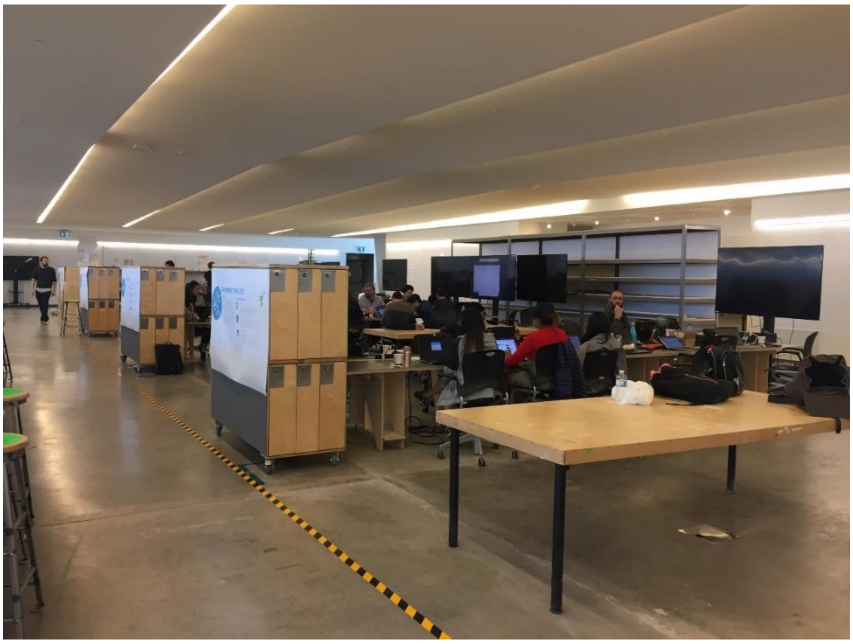

Figure 5.9. Open plan layout of the environment from SG 2018, Daniel's Faculty of Architecture, University of Toronto (Öykü Acıcan).

Finding 5. Absence of hierarchy can provide a better dialog between the contributors to the workshop, increase the responsibility of the participants, and improve the learning process. The sharing and community support after the workshops increase the pace and range of learning computational design.

Finding 6. The visual and physical interactions between the participants from different workshops help increase their awareness of various design problems, tools, and methods as well as the design proposals.

5.5. Effects of Rapidness

SG workshops take place during the course of four days, which can be considered as short duration, so the workshops require to be conducted rapidly. Several strategies were observed in SG to attain rapidness, such as using and combining state-of-the-art tools and techniques that enable maximum pace to complete the workshop process on time. In addition, social approaches are present to reach rapidness, such as brainstorming and collaborative working.

The urgency of completing a design task in a short duration was observed to have a positive effect on collaboration. Interviewees state that the participants tend to collaborate easier when there is a lack of time. According to interviewee 8, the rapidness of the workshops results in a decrease in individual concerns and an increase in group participation. When the aim is completing the task, instead of gaining personal benefits, participants tend to be more committed. According to interviewee 10, the team can collaboratively produce and apply ideas faster, resulting from more productive teamwork. Working intensely in the short duration of time may result in tiredness and strain, but it is the intense and rapid working that enables the emergence of new learning opportunities from each other in a different context than a usual and daily learning environment.

According to the interviewees 3, and 7, the short duration of the workshops encourages the participation and gathering of the specialists to conduct experimental projects. Usually, it is hard for specialists from different fields to meet and conduct a project together. However, unlike the long design processes, SG workshops require a very short investment of time. Interviewee 7 states that the design processes that take a long time may bring over-investment, and that may result in a conservative perspective. Short duration, on the other hand, enables the specialists, tutors, and participants to become less scared by the risk of becoming unsuccessful. Interviewee 3 states that contributors can experiment on various topics very quickly that would generally take years. Therefore, even specialists who are resistant to conduct very experimental projects agree more comfortably to be a part of the SG clusters.

There are conflicting ideas about the effects of rapidness on the research and learning process. Interviewees 2, 3 and 9 state that it is the long background research that gives the depth of a workshop. In contrast to rapidness, slow and focused research is needed for an interdisciplinary synthesis of knowledge. Interviewee 3 states that both rapid and slow research is needed in order to conduct a workshop and the two types of research feed each other. Although the tutors and experts take part both in the slow and rapid phases of research, participants take part only in the rapid phase during the workshops. In the short duration of SG, knowledge transfer to the participants may not be complete. There is a risk that a participant may leave the workshop with superficial conceptions and incorrect practical knowledge. However, interviewee 10 states that although SG workshops may not be long enough to learn about a new concept in-depth, the significance of the workshops are to show the designers what they do not know about and bring a new horizon to the participants to adjust themselves for an interdisciplinary vision.

> Finding 7. While rapidness may cause the lack of learning certain concepts in-depth, rapidness may also densify the experimental character of the SG workshops, expands the horizon of the designers, and strengthens the experiential learning.

5.6. The Importance of Customization for Individual Learning

Several SG workshops demand from the participants to have an individual design output. There are several reasons for the need of individual designs, such as experimenting with certain tools through individual design projects (*Mind Ex Machina*), comparing the performance of different design outputs that are collected from the participants (*Materials as Probes*), and assembling the individual design outputs of the participants to produce a coherent whole (*Inside the Black Box*). Designing and producing an individual outcome during the workshops is defined as customization by the interviewee 4.

Interviewee 4 states that in SG, individual learning can be achieved by demanding individual tasks from the participants and providing “personal space”. The workshops where the participants are required to contribute to one project, such as building a large structure, may restrict the learning process as there is less opportunity for customizing. While collaborative working makes it possible to produce a complex design outcome, individual working can be a stronger strategy for fully grasping a subject in detail. While working individually, participants have a one-to-one experience during the complete design process on their own, as opposed to team-working, where participants undertake partial duties.

The participants of the SG workshops can gain knowledge that would be the most beneficial for their jobs, career, or research by customizing the provided tools and technology during the workshops. Thus, different participants may gain different knowledge from the same workshop. The SG 2018 workshop named "Mind Ex Machina" can be considered as an example for customization by experimenting on a provided tool. The participants were asked to plan their personal project by using a specific robot, to find novel ways of human-robot interaction. In the workshop, participants worked for different objectives that they selected according to their own research interests.

It was observed and experienced during SG that individual tasks help to increase the responsibility for the participants. According to the interviewees, through designing or producing individually, participants can be more competent about a design task, and that helps to increase the depth of learning. Some of the SG workshops demand from the participants to produce individual design outputs to be used as data through which to conduct research. For instance, the aim of the SG 2018 workshop named "Materials as Probes" is experimenting with the thermodynamic behavior of a paraffine wax material, whose transparency changes in different material phases, in customized façade elements that have different geometries. Participants individually designed and produced façade elements with customized forms and patterns, which were then filled with the stated material. Afterward, wireless sensors were placed into the customized façade elements for collecting thermodynamic data from the varying forms of the façade elements. Cluster champion Christopher Connock expresses that the final experiment of the cluster would bring hypotheses about the melting behavior of the wax material and possible forms that would emerge in the customized elements. [118] Finally, participants were able to see the façade elements one next to another and

[118] Materials as Probes [Video file]. (2018) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2018workshops.

experientially learn about the melting behavior of the material depending on the form. Participants could actively produce a single design output and experiment on the material behavior of the wax individually. Customization in this case provided the participants to have a deeper understanding of the material behavior and to feel more included in the experimentation process.

Figure 5.10. Customized façade elements, Materials as Probes, 2018, (Öykü Acıcan)

> Finding 8. While customization enables individual learning where participants can specialize on a certain skill, collaborative learning enables learning from a collective process that may lack specialization of the participants on a single skill.

5.7. Interactiveness for Experiential Learning

Interactiveness is a significant characteristic of the contemporary SG workshops and refers to the interactivities between participants, tutors, tools, and materials. It was observed that being in an information exchanging environment helps the participants to connect and construct new knowledge. In SG, each contributor can have social and technological interactions.

According to interviewee 2, the interactions between human-human, human-machine, and machine-machine play a vital role in the learning process because it is the dialogue and the rapid feedback between two actors that provide learning. Interactivity between participants and tutors has the potential to give rise to informal learning. According to Boud et al., informal learning, or "peer learning" is a "two-way reciprocal learning activity" that occurs when individuals "work with each other to teach and to learn from each other".[119] To illustrate, the goal of the SG 2016 workshop named "Sensory Detectives" is to build a modular and environmentally sensitive structure. A small part of the workshop involves textile design for the covering of the modules. Katrina Gaskin is a textile expert, and she shows the participants how to use the different textile fabrications with the modules. Gaskin expresses that the participants ask unexpected questions that she has not thought about, and with their different backgrounds, participants can reflect upon and apply Gaskin's knowledge.[120] The interaction between Gaskin and the participants enable the participants to add knowledge to their repertoire and enable Gaskin to gain new perspectives.

Figure 5.11. Textile Coverings by different participants, Sensory Detectives, 2016[121]

The interaction between the participants and tools help to expand the cognitive capacities of designers. According to interviewee 1, designers have learned to think systematically and symbolically as well as spatially, due to the increasing interaction

[119] Boud, D., & Lee, A. (2005). 'Peer learning'as pedagogic discourse for research education. *Studies in Higher Education*, *30*(5), 501-516.
[120] Sensory Detectives [Video file]. (2016)
[121] Prohasky, D. (n.d.). [Textile Coverings of the Modules]. Retrieved from http://urbaniot.arup.io/resources/UrbanIoT_framework-presentation_RMIT-SIAL_DanielProhasky.pdf

between human and machine in SG workshops over the years. Omer Akin defines symbolic representations as the mathematical relationships between the abstract physical entities such as forces and energy.[122] Dino explains that the physical entities are also related to the definition of performance such as heat transfer, light, and sound distribution.[123] Developing abstract relationships with the surrounding forces and parameters when designing is one of the most important aspects of computational design. Besides, symbolic thinking enables humans to understand the inner processes of the machines and design collaboratively with them, rather than using them only as a tool.[124]

Interaction between the participants and the computational design tools in SG enables new ways of learning by different methods of communication between humans and machines. Interviewee 2 states that the interaction between a machine and a human should be similar to the interaction between human and a human for a better learning; and that is achieved by responding and interacting in real time. According to Daniel Piker, who is an SG cluster champion and founder of the structural plugin "Kangaroo", flexibility and playfulness of software makes it enjoyable to use and the interaction of the designer with that software helps to learn by encouraging experimentation and the development of new ideas. [125]

Different uses of digital fabrication tools and methods can be observed in the SG workshops. Many processes and calibrations should be achieved in order to realize the customized fabrication processes where human-machine interaction is vital. To illustrate, the SG 2016 workshop named "mud, textiles, and robots for large structures" aims to test a new construction method by spraying mud on textile

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[122] Akin, O., & McCracken, M. (2001). Variants in Design Cognition. In C. Eastman (Ed.), *Design knowing and learning: Cognition in design education* (pp. 105–124). Atlanta, GA: Elsevier.
[123] Gursel Dino, I. (2012). Creative Design Exploration by Parametric Generative Systems in Architecture. METU Journal of the Faculty of Architecture.
[124] Menges, A., & Ahlquist, S. (Eds.). (2011)
[125] Peters, B., & Peters, T. (Eds.). (2013).

formworks.[126] A collaborative robot (Cobot) was used to achieve the stated objective precisely. The robot needed to identify the surface in detail and decide where to spray the mud. The mechanism and the movement axes of the co-bot required to be well-grasped by the designers to be able to calibrate its steps. Participants learn how to translate the information to the language of the robot, and the movement of the robot constitutes the feedback for interactive learning. By interacting with the robot in real-time, participants could have a better understanding of how to calibrate the robot for a complex task and how to transfer information to a device that works different than a human.

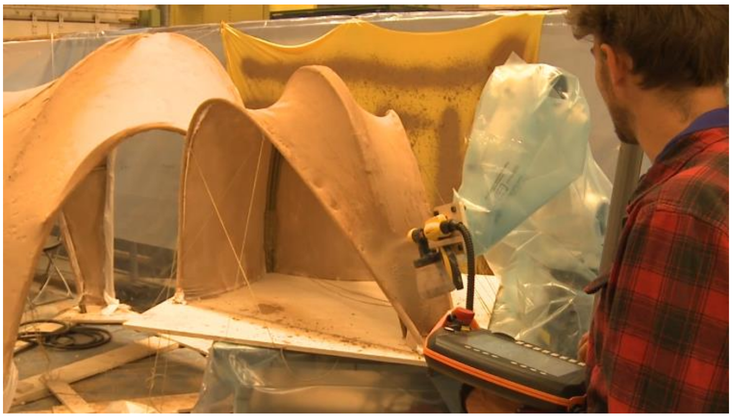

Figure 5.12. Cobot, spraying mud on the framework.[127]

Increased interactions between human and machine over the years in SG brought in an increased understanding of how to collaborate more and better with machines. For example, Mind Ex Machina is a research project that experiments how the interaction between the participants and robots are taking place. Applying machine learning to robots shows a significant increase in the interaction between humans and robots. In Mind Ex Machina, robots show intelligence by diverse objectives, such as understanding gestures of humans, playing Jenga with a human and continuing a

[126] Mud, textiles and robots for large structurs [Video file]. (2016) Retrieved December 25, 2018 from https://www.smartgeometry.org/sg2016workshops
[127] Mud, textiles and robots for large structurs [Video file]. (2016)

sketch of a human by drawing further.[128] In this case, robots have more right to speak and give design decisions. Robots adapt to certain goals with the interaction by responding to real-time input. From this development, it is understood that robots have transformed from being a prototyping and fabrication tool to sophisticated, interactive collaborators of humans. This change induces new learning methods by the increased potentials of interactive experimentation.

Figure 5.13. Robots continuing from the sketches of humans[129]

Interaction between multiple machines is called machine collaboration that is achieved through multiple robots and computers working together.[130] Machine collaboration brings in processes that cannot be achieved by a single machine. Complex computational design subjects such as automation, emergence, and complexity are experimented in some of the SG workshops by using interactive tools that transform the abstract subjects into tangible and observable entities. For instance, the SG 2016 workshop named "Martian Autonomous Robot Swarm (MARS)" is a research project about automated construction through machine collaboration in the extreme environments of Mars. One of the workshop champions explains the system as being composed of multiple little simple devices together creating an object, and that the

[128] Mind Ex Machina [Video file]. (2018) Retrieved December 25, 2018 from https://www.smartgeometry.org/sg2018workshops
[129] Smart Geometry 2018 Sketch RNN Exquisite Corpse [Video file]. (2018) Retrieved March 10, 2019 from https://www.are.na/block/4133551
[130] Deutsch, R. (2017).

idea is inspired by natural systems which include complexity and emergence.[131] Instead of using solely virtual simulations, embodied computation was used through the materialization tools. While the robots have simple goals on their own, communication between the ten robots create the complex construction process and automation. It can be concluded that the interaction between multiple machines helps the participants to grasp the concepts such as complexity and automation by constructive and experiential learning.

Figure 5.14. MARS from Smartgeometry 2016[132]

Finding 9. While the interaction between the *human and human* enables peer learning, interaction between the *human and machine* enables a better understanding on the environment through symbolic thinking and that results in performative design learning.

[131] MARS: Martian Autonomous robot swarm [Video file]. (2016) Retrieved December 20, 2018 from https://www.smartgeometry.org/sg2016workshops.
[132] Ibid.

CHAPTER 6

CONCLUSION

This research aimed to identify the aspects and mechanisms behind computational design learning for architects with a case study on the SG workshops. The stages of SG workshops and the changes in the agenda of the workshops over time were explained. The aspects that have an impact on the computational design learning in SG were explored. These aspects, namely *research, interdisciplinarity, computational design tools, democratization, rapidness, customization, and interactiveness,* were discussed in Chapter 5: Findings. The qualitative research strategy was used to provide multiple perspectives by the variety of data sources. Besides, participant observations and semi-structured interviews enabled unexpected insights to the findings. The analysis of different data sources resulted in obtaining more valid findings.

The main purpose of this thesis is to explore, understand, and conceptualize the contemporary aspects of computational design learning, which is gaining importance in architectural education. The literature review has revealed that there is a general scarcity of qualitative studies on extracurricular computational design learning from multiple cases. The extant studies on computational design learning are based on single cases, usually long-term courses, certain developed tools and methods, and the learning outcomes of the students. This indicates a need to understand the experiential and rapid learning methods of workshops as there can be several differences from the slow, long-term courses that investigate a single tool or strategy. Besides, while one course may not be enough to represent the computational design field, multiple workshops distributed in years have the potential of representing the field. In doing so, the main research question was formulated as follows:

- *What are the aspects and mechanisms behind computational design learning for architects and how are those mechanisms conducted?*

As discussed in the *Findings* section, the importance of experimentation and research in SG increased over the years. The change in SG workshops over the years can be attributed to a certain level of maturity computational design has reached, which expanded its attention from mere form-finding to other factors that can inform design for both synthesis and analysis. According to Agkathidis, computational design has been long charged for being self-indulgent and stylistically driven, due to its initial fascination with complex geometries during the early 2000s.[133] While computational form-finding continues to be a fundamental issue for architecture and design, involving other aspects to the design process, such as research and interdisciplinarity has potential for learning about performance-based design in the way it considers environmental data as an inseparable part of the design process such as the design's environmental footprint, costs or occupant comfort.

This study has demonstrated that computational design education should be interdisciplinary and collaborative, due to the very interdisciplinary nature of the field. SG workshops prove that knowledge, methods and tools from various disciplines need to be integrated to utilize the full potential of computational design and gain meaningful results. Collaborative working is a practical and productive method for interdisciplinary computational design learning as it might be un-practical for an individual to gain several disciplinary knowledge by herself. It was discussed that the contributors of an interdisciplinary team may know little about each other's background knowledge. Therefore, an awareness about the limitations of a single discipline and more interaction between the individuals from different disciplines can help the contributors to be more open-minded to the tools and methods of different fields of knowledge. Computational design courses in the architectural curriculum can also be more effective if an interdisciplinary approach is used. Students from different disciplines can participate in computational design courses and studios where

[133] Agkathidis, A. (2015). Generative Design. London: Laurence King Publishing

interdisciplinary collaboration can be taught from the early stages of architectural education.

Producing a community, having equality between the participants, and sharing knowledge are some of the important social factors behind the SG workshops. These social factors can be related to democratization. Democratization enables the participants to perceive and realize that all the contributors are equals. That may help to overcome the prejudices and to be more open to learning from each other. Democratization also refers to equal accessibility to the *computational design tools*. Accessibility of the tools and equal opportunities of all the participants are essential educational values of SG. It was previously mentioned that interactive use of computational design tools accelerates the processes of experimentations, discoveries, and research during the SG workshops. By having equal access and opportunity of interaction with the tools, participants can have the confidence of using the computational design tools, which contributes to learning-by-doing. Similarly, a democratized education can be applied for the curricular computational design education in which the hierarchy between the students and teachers are decreased. This may be achieved by providing multiple clusters of students with more instructors. When the number of instructors becomes closer to the number of students, overcoming the hierarchy may become easier. Moreover, environments that provide visual interactions and an easier access to the computational design tools can provide a democratized computational design education.

Findings indicate that the different SG workshops focus on different aspects. Although the SG workshops have several characteristics in common, such as the shared space, team-working, interdisciplinarity, and an emphasis on computational design; the conducted research per each workshop may differ dramatically. That difference may result in different skills to be gained by different participants. For instance, while a workshop where participants experiment with a specific computational design tool focuses on customization, a workshop where participants construct a large structure as a team focuses on collaborative working. In the former workshop, participants do not have the chance of working together because of the individual tasks. In the latter workshop, however, participants may not have the chance to specialize in a certain task because of working dependent to each other. These two workshops add different learning outcomes to the participants. While a participant from the former workshop gains individual competence of a tool/method/algorithm, another participant from the latter workshop experiences taking part in a large-scaled design project and gains the competence of being involved in a complex collaborative design process. Providing several projects in one computational design class can help the architecture students to experience different aspects of computational design through collaborative working and individual working.

This study has shown that both instructive and experiential learning take place in an SG workshop. Workshops involve a short instructive stage where the tools and objectives are taught. Afterward, participants design an artifact, or experiment with certain computational design tools. However, the experimental phase dominates the agenda of the workshops. In SG, as learning happens through experiences that are connected to the surrounding environmental factors and individuals, experiential learning is encouraged more than instructional learning. Due to rapidness, there is not time to have enough instructive learning in the SG workshops, and that may limit the learning process. On the other hand, while the depth of the learning is limited in SG workshops, breadth of learning is accelerated through the interdisciplinary interactions and the accessibility of the tools. SG provides experiential and interactive computational design learning that is beneficial from a constructionist pedagogical point of view. If there is sufficient instruction, an in-depth learning can also be achieved. There must be enough instructional learning before the experimentation and collaboration for fully grasping certain subjects, tools, and methods, and the experimental phase should follow the instructive phase. In conclusion, computational design learning requires a balance between instructive and experiential learning.

This thesis has explored the aspects and methods of computational design learning from multiple workshops of SG over the years. This study has shown that the extracurricular learning environments such as the workshops enable the emergence of several aspects that affect computational design processes and learning. Together with the previous discussions, it is possible to say that computational design education needs to be a constructionist process where learning-by-doing and experiential learning are balanced with instructive learning. Besides, it can be concluded that computational design education cannot be taught under a single discipline. This study has shown the presence and emergence of the conditions and aspects that have the potential of improving computational design teaching in architectural education. These can be, including experimentations to the syllabus of computational design courses, achieving equality between the educators and learners, enabling a better access to the computational design tools, providing computational design courses that accepts students from different departments, giving equal weight to customization and collaboration through individual and collective tasks, and providing a higher interaction between the constituents of a computational design course.

The learning aspects and strategies that were explored in this research is based on the participant observations, interviews with computational design experts and educators, and the analysis of the past workshop video recordings and textual documents. Further research might also involve the interviews and surveys that are directed to the workshop participants as a data source. The perspectives of the participants would provide a better understanding of the learning aspects, as the participants constitute a major percentage of the learners in an SG event and a workshop.

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APPENDICES

A. Informed Consent Form

This study, is a qualitative research study by Öykü Acıcan on “Computational Design Learning in Smartgeometry Workshops” which is conducted by Associate Prof. Dr. İpek Gürsel Dino, Department of Architecture, Middle East Technical University

What is the aim of the study? The aim of the study is to collect data about the processes of computational design learning and interdisciplinarity in Smartgeometry workshops and its effects to the agenda in the computational design field in architecture. If you agree to participate the study, you are expected to answer 5 questions of an interview about Smartgeometry. It takes approximately 15 minutes to participate this research.

What is expected from you? We are expecting to hear your experiences and observations on Smartgeometry in the framework of the 5 questions of a semi-structured interview.

How will we use your answers? Participation in the study must be on a voluntary basis. No personal or institutional identification information is required in the interview. Your answers will be kept strictly confidential and evaluated only by the researcher. The obtained data from the participants will be evaluated collectively and they will be used for scientific purposes. The data you have provided will not be matched with the information collected in the informed consent form.

Information about the Participation: The interview does not contain questions that may cause discomfort in the participants. However, during participation, for any reason , if you feel uncomfortable, you are free to quit at any time. In such a case, it will be sufficient to tell the person conducting the survey (i.e., interviewer) that you have not completed the interview. After all the questionnaires are collected back by the data collector , your questions related to the study will be answered.

For Further Information : We would like to thank you in advance for your participation in this study. For further information about the study, you can contact Associate Prof. Dr. İpek Gürsel Dino from the department of architecture (Room: R85; Tel: +90312210 2203; E-mail: ipekg@metu.edu.tr)

I am participating in this study totally on my own will.

(Please return this form to the data collector after you have filled it in and signed it).

Name Surname	Date	Signature
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