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THE ENGINEERING DESIGN GRAPHICS

Journal

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About the Journal
The Engineering Design Graphics Journal serves as the official journal of the American Society for Engineering Education, Engineering Design Graphics Division and provides a professional publication for educators and industry personnel associated with activities in engineering, technology, descriptive geometry, CAD, and any research related to visualization and design.

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Message from the Editor

Welcome to the New Normal

By Robert A. Chin
East Carolina University

On Aug 24, 2009, the online-only Engineering Design Graphics Journal (the Journal) was launched (see http://www.edgj.org) following an eighteen month self-study. The self-study began Feb 2, 2008 when the then Engineering Design Graphics Division Executive Committee Chair, Kathryn Holliday-Darr, issued a challenge in response to division member concerns and complaints: "…make suggestions on how to fix the problem". One of the major concerns was for the sustainability of the Journal.

Following the Feb 2, 2008 challenge, an online dialogue took place among division members regarding the immediate future of the Journal. During the division's 2008 annual conference, a five member ad-hoc committee was formed to look into the various options for publishing an online-only journal. At the division's 63rd annual mid-year conference, La Verne Abe Harris, the journal's editor and the division's director of publications, proposed adoption of Open Journal Systems (OJS) as the means for publishing the Journal based on recommendations by the five member ad-hoc committee. By the division's 2009 annual conference, and because of support provided by East Carolina University and the availability of a graduate assistant, an OJS online-journal test site had been launched and six issues of the journal, including the two most recent issues, volume 73 numbers 1 and 2, had been posted. At the conference, I assumed responsibility as the division's director of publications and editor of the Journal. During the division's 64th mid-year conference, in addition to reporting that the journal had been officially launched following secession of testing, it was reported that a total of 27 issues of the journal had been posted.

Prior to the publication of volume 73, all issues of the Journal were printed and physically mailed to those entitled to issues. As well, and up through the last issue published, volume 73 number 2, all manuscripts were submitted as attachments to an email message and the editorial process was handled by means of emailing attachments: a rather cumbersome process at the very least.

Key to the successful production of any journal in transition includes ensuring authors can continue negotiating the submission, editorial, and publication process; reviewers can continue evaluating manuscripts; and editors can continue working with authors and reviewers with relative ease. For this reason, the Journal is presently pursuing a blended approach to publishing the journal. A successful transition will involve getting authors and reviewers trained and acclimated to the new normal of the fully online process. A year will be set aside to complete this transition. That is, for the next year or so, the Journal will continue accepting manuscripts the old fashion way and reviewers will continue receiving manuscripts for review the old fashion way. However, authors and reviewers will be encouraged to use the system. Delivery of the Journal however will be online. During this one year period, it's anticipated that authors and reviewers will transition to the new normal.

I look forward to working with the members of the division, encourage authors to check out our site and submit their manuscripts, and welcome inputs that will help us succeed in this endeavor. Your willingness to negotiate the new normal will ensure our success.

Message from the Chair

"A Christmas Carol"

Patrick E. Connolly
Purdue University

It is a privilege and an honor to be serving as the Engineering Design Graphics Division Chair for this year! We had a great time and a wonderful Midyear meeting in beautiful Erie, PA last month. The presentations were excellent and the 'conviviality' was (as always) outstanding. Once again, special thanks need to be extended to Kathy Holliday-Darr and Judy Birchman, who worked so hard and put in many, many hours to ensure a fantastic conference.

As we continue to move forward in the Division with an eye to the future, one of the potential action items that has been discussed over the past year is changing the name of the Division to reflect who and what we are becoming. You should have all received an email from Mary Sadowski (sent 11/16/09) regarding a Delphi study that we are conducting on this topic, with the goal of identifying consensus from the Division members. It will be a four-round Delphi, and we will need the input from as many of you as possible to ensure the validity of the results. Please respond to Mary's email if you are willing to participate – we need you! If you signed up to participate at the Erie Midyear, then you do not need to reply to the email.

Speaking of the Midyear, I decided to look at the topics of the presentations in order to get a feel for where our people are researching, and to possibly get a better idea of our direction. There was a strong focus on web applications and techniques, including talks on online learning in multimedia, blended learning/instruction in engineering graphics, and online publishing. This recurring emphasis over the past few years of Annual and Midyear presentation topics highlights our Division's focus on understanding and strategically applying technology in our classrooms and applications. Many different research areas were highlighted, including lightweight CAD formats, data transfer issues, and augmented reality. As always, we enjoyed a number of presentations regarding effective instructional methods, such as rapid prototyping, information scaffolding, and simulation. One of the strengths of the Division continues to be our attention to the principle of being premier instructors of engineering graphics and graphic applications. It was also good to see so many presentations (at least five) that looked at spatial ability and spatial skill development. I feel this remains a critical area of development for our students and in our research. We also enjoyed presentations in 'current events' areas – emerging trends in graphics, diversity, curriculum development, and accreditation. Bundled all together, it seems to me that the presentation topics at the Erie Midyear meeting do a pretty good job of taking a topical snapshot of who we are as graphics practitioners. We have the challenge of maintaining our presence in graphics past, present, and future (sort of a graphics version of Ebenezer Scrooge in Dickens' 'A Christmas Carol'!).

Looking forward, I see a great future for our field in both research and classroom excellence. As the 'keepers of the gate' for engineering and multimedia graphics education, we have the solemn, challenging, and wildly enjoyable responsibility to continue the pattern of outstanding leadership and scholarship that

Message from the Chair

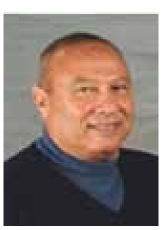
our distinguished forbearers in the Engineering Design Graphics Division have established as our foundation. This is a mighty and sometimes daunting quest that we have embarked on, but that is why we chose the professions that we are in. I am confident that as we strive to continuously move forward with our best efforts, that we will be able to touch lives, educate, and prepare the next generation of graphics practitioners for their exciting futures.

ENGINEERING DESIGN GRAPHICS DIVISION OFFICERS

Officer Nominees

Aaron C. Clark
for Vice-Chair

Aaron C. Clark is an Associate Professor of Technology, Design and Engineering Education within the College of Education and is the Director of Graduate Programs for the Department of Mathematics, Science, and Technology Education. He received his B.S. and M.S. in Technology and earned his doctoral degree in Technology Education. Dr. Clark has worked in both industry and education, including administration at the regional college level. He lived and worked in Virginia, Tennessee and Maryland before coming to North Carolina. His teaching specialties are in visual theory, 3-D modeling, and technical animation. Research areas include graphics education and scientific/technical visualization. He presents and publishes in both technical/technology education and engineering. He has been and continues to be a Principle Investigator on a variety of grants related to visualization and education and has focused his research in areas related to STEM curricula integration. Dr. Clark has been a member of the Engineering Design Graphics Division of the American Society for Engineering Education (ASEE) since 1995; and has served in leadership roles and on committees for the Division since that time. He is also an active member of the K-12 Outreach Division within ASEE. Dr. Clark is recognized as a Distinguished Technology Educator by the International Technology Education Association.



Moustafa Moustafa
for Vice-Chair

Professor Moustafa joined the Mechanical Engineering Technology department at Old Dominion University in Norfolk, Virginia in August 1979. Professor Moustafa received his BS in Mechanical Engineering from the Higher Institute of Technology in Egypt in 1964. He received a Masters of Engineering degree in Machine Design from the University of Illinois, 1976 (Mechanical and industrial Engineering Dpt.) and another Masters of Engineering in Structures and Stress Analysis from the University of Illinois in 1979 (Aeronautical and Astronautical Engineering Dpt.).

Moustafa completed the Ph.D. course requirements in Structural Analysis in Civil Engineering at Old Dominion University. Professor Moustafa's interest is in the area of Mechanical Systems design such as computer-aided design, computer graphics, 3-D solid modeling, stress analysis and design for safety. As a certified manufacturing engineer, Professor Moustafa is active in professional societies such as SME, ASME, ASEE.

During his 30 year career at Old Dominion University, Moustafa has served in many executive capacities, received numerous awards, and presented a number of papers in scientific conferences.

Moustafa received the Frank Batten award for industrial partnering, received numerous student awards for favorite professor in engineering, and numerous service awards from professional organizations.

Moustafa founded the Autodesk authorized training center at Old Dominion University and served as its director for 15 years. Moustafa taught several hundred continuing education classes training professionals in AutoCAD and other Autodesk software products.

Moustafa has published and presented several technical papers in scientific and engineering journals and conferences.

As a consultant, Professor Moustafa has worked with local and out of state companies on projects such as stress analysis for a local locomotive manufacturing company to solve a problem on failure of the main shaft, analysis for a computer security company in New York for work done in Saudi Arabia, transformed a medium size machine shop from traditional manufacturing processes to CAD-CAM. He also participated in a number of projects with the Technology Application Center at Old Dominion University.

Professor Moustafa has served as an independent expert witness in court cases involving industrial safety issues.

William Howard
for Membership Chair

William E. (Ed) Howard is in his fifth year as a faculty member in the Department of Engineering at East Carolina University, where he teaches graphics, computer applications, and mechanics courses. Prior to moving to ECU, he worked in industry for 14 years at Thiokol Corporation, Spaulding Composites Company, and Sta-Rite Industries, and was a faculty member in the Mechanical Engineering Department at Milwaukee School of Engineering for nine years. He is the author of two textbooks: An Introduction to Solid Modeling Using SolidWorks (with Joseph Musto), and Engineering Computations: An Introduction Using MATLAB and Excel (with Joseph Musto and Richard Williams), both of which are published by McGraw-Hill.

Kevin Devine
for Membership Chair

Kevin Devine is an Assistant Professor in the Department of Technology at Illinois State University. Kevin has a Doctorate of Education degree in Curriculum and Instruction and Bachelor of Science and Master of Science degrees in Industrial Technology. Prior to becoming an educator, he was a Senior Engineer in CAD/CAM Systems and NC Systems in the aerospace industry. Kevin's teaching areas include engineering graphics and solid modeling, robotics technology and machining & CNC programming. Kevin's research interests include exploring ways of using modern engineering technology to teach STEM principles. Kevin received the 2008 Editor's Award from the EDGJ for an article describing his research using solid modeling software to help teach mathematics to high school students. In addition to being a member of ASEE/EDGD, Kevin serves on the Board of Directors for the Illinois Drafting Educators Association (IDEA).

Ron Paré
for Program Chair

Ronald C. Paré is a Professor Emeritus of Engineering Technology, College of Technology, University of Houston. Professor Paré has BSME and MSME degrees from Washington State University and California State University-Los Angeles. He taught Computer-Aided Drafting and Design at the University of Houston from 1983 until retirement in 2005. Prior to his University of Houston position, Professor Paré was an Associate Professor and senior administrator at Cogswell College in San Francisco and Seattle for ten years. Professor Paré began his teaching career in 1968 at California State Polytechnic University in Pomona, where he taught Engineering Graphics and helped initiate the Engineering Technology programs in the California State University System. Professor Paré's research interest is the Industrial and Educational Applications of Computer Graphics and Descriptive Geometry. He is the author of a textbook entitled Descriptive Geometry, which is used at over 140 universities and colleges in the US, including six in Texas. Professor Paré has taught CAD on Television and via the Internet.

Professor Paré is a life member ASEE and ASME.

Officer Nominees

He has served in elected positions of the Engineering Technology and Engineering Design Graphics Divisions of ASEE and the Mechanical Engineering Technology Department Heads Committee and the Board on Education of ASME. He currently represents ASME as a Mechanical Engineering Technology and Drafting Design Engineering Technology ABET Program Evaluator.

Sheryl Sorby
for Program Chair

Dr. Sheryl Sorby is a Professor of Mechanical Engineering-Engineering Mechanics and Director of Engineering Education and Innovation at Michigan Technological University. She recently served as a Program Director within the Division of Undergraduate Education at the National Science Foundation. Dr. Sorby received a Bachelor of Science in Civil Engineering in 1982, a Master's in Engineering Mechanics in 1985, and a PhD in Mechanical Engineering-Engineering Mechanics in 1991, all from Michigan Technological University. She was Michigan Tech's first graduate exchange student, attending the Federal Technical Institute in Zurich, Switzerland for the 1983-84 academic year. She has been on the faculty at Michigan Tech since 1986, starting first as an Instructor while completing her PhD degree and later joining the tenure-track ranks in 1991. Dr. Sorby is the former Associate Dean for Academic Programs in the College of Engineering and the former Department Chair of Engineering Fundamentals at Michigan Tech. Her research interests include graphics and visualization. She has been the principal investigator or co-principal investigator on more than $5M in external funding, most from the National Science Foundation for educational projects. She was the recipient of the Betty Vetter research award through the Women in Engineering ProActive Network (WEPAN) for her work in improving the spatial skills and ultimately the success of women engineering students. She has also been a leader in developing first-year engineering and the Enterprise program at Michigan Tech and is the author of numerous publications and several textbooks. Dr. Sorby currently serves as an Associate Editor for ASEE's new online journal, Advances in Engineering Education. In 2007, she received the Distinguished Service Award from the Engineering Design Graphics Division of ASEE. She was the recipient of the Dow Outstanding New Faculty Award and the Distinguished Teaching award, both from the North Midwest Section of ASEE. Dr. Sorby is a member of the Michigan Tech Council of Alumnae. Her proudest achievement is the success of her three children. Her two daughters are pursuing graduate degrees in engineering and her son is still finding himself.

2009 Distinguished Service Award

William A. Ross

Presentation Speech

Dear Members of the Engineering Design Graphics Division:

Thank you for presenting me with this years EDGD Distinguished Service Award. I am both humbled and honored by this recognition and regret that I am not able to be there for the presentation. Although it has not been possible for me to maintain active participation at the Division's annual and midyear meetings for the last 5 years, I remain as loyal to the Division and its members as I was when I first joined in 1981. I can't believe its been that long! Where does the time go?

My first EDGD midyear meeting was in Pittsburg, PA back in January of 1984. Garland Hilliard, my boss and mentor at N. C. State at the time, encouraged me to write a paper and make a presentation on the new 3-D CAD instruction that we were developing at State. Boy was I nervous! As I look back, it is easy to see why I became an instant fan and now a loyal longtime advocate for the Division at that meeting. Colorful and now 'legendary' figures like Bob Larue, Mary Jasper, Larry Goss, Frank Croft, Jon Duff, Jack Brown, and many others, made me feel welcome and valued. No pretenses and no airs! As Tim Sexton said in his acceptance speech last year, "I never knew that there were so many other people that were as passionate about graphics as me.". Personally, it was great to suddenly discover a professional identity and home. I have never wavered from that identity.

In the past, the Division has honored me by nominating and electing me to serve for two terms as Director of Programs, from approximately 1989 through 1994. I learned so much as Director of Programs and had the opportunity and privilege to orchestrate and help organize technical sessions and programs for many annual and midyear meetings. It was a terrific way to get to know many of you. I was also nominated and elected to serve as Vice Chair of the Division for 1993-94 followed by a year as Chair of the Division in 1994-95. What a wonderful honor and career rewarding experience.

Before finding a niche in engineering graphics, I had numerous experiences that helped to define my career. I joined the U. S. Air Force and became involved in technical training. After finishing college, I was employed as a young high school drafting teacher, a community college mechanical drafting instructor, and later as an architectural designer and project manager at a construction firm. Since discovering my professional niche at the EDGD midyear meeting in 1984, I've had twenty five marvelous years of pursuing a passion for graphics at N. C. State and Purdue Universities. Participating in the evolution of engineering graphics starting in the industrial age and evolving into the three-dimensional interactive information age has been a career challenging quest. Engineering graphics continues to evolve through this critical shifting period of time and we want to 'get it right'.

Without doubt, the most memorable part of my time in higher education has been spent with students. I didn't always like every one of them, but I loved them all! After all, they were the reason I was there. However, without the freedom and support to develop and evolve new teaching strategies and methods through our supporting universities, colleagues, and especially professional organizations, we would have dried up and blown away long ago. With the support and encouragement of organizations like EDGD, I am delighted to have developed new instructional materials, written numerous grants and technical articles, presented papers at more than 50 conferences and meetings around the world, and authored or contributed to nine text books with more than 20 of my professional colleagues. What a blast! In addition to the support of two marvelous universities and many fantastic colleagues, I am particularly indebted to the Engineering Design Graphics Division for making my life's work possible. In fact, until you unanimously tell me to stop, I am so inspired by this award that I plan to continue to develop and publish solid modeling instructional materials and teach part-time well into the future!

Like many other award winners, I went back and reviewed the list of more than 50 DSA honorees. It is a long list of distinguished, creative, and more recently, eclectic professionals that support the technology and engineering fields. I am proud to say that I got to shake hands and thank many of those individuals. Unbelievably, I now find myself on a list of people that I have admired and looked to for inspiration. Deserved or not, that's a heady feeling.

My thanks to Pat Connolly, colleague and co-author, for graciously agreeing to present these comments and accept the EDGD 2009 Distinguished Service Award in my absence. Finally, thank you all…those present tonight and those unable to attend the presentation of this treasured distinguished service award.

Sincerely,

William A. (Bill) Ross

Generating Alternative Engineering Designs by Integrating Desktop VR with Genetic Algorithms

Magesh Chandramouli, Gary Bertoline, Patrick Connolly
Department of Computer Graphics Technology
Purdue University, West Lafayette, IN 47907

Abstract

This study proposes an innovative solution to the problem of multiobjective engineering design optimization by integrating desktop VR with genetic computing. Although, this study considers the case of construction design as an example to illustrate the framework, this method can very much be extended to other engineering design problems as well. The proposed framework generates optimal solutions for the problem of construction design, which is becoming an increasingly complex problem due to the multitude of factors involved in the process. This study places special emphasis on the modeling of the scenes within the virtual world from the design perspective. Even though genetic algorithms (GA) have been used by professionals in diverse disciplines to optimize conflicting objectives, these provide the end user with a pool of solutions rather than a unique solution that can be implemented. Hence, this study proposes a desktop VR framework that serves as a visualization tool to aid decision makers to better evaluate the alternative solutions from the Pareto set resulting from the GA process. Modeling alternative scenarios is formulated as an optimization problem wherein design configurations are generated using genetic algorithms. With the goal of sustainable and non-destructive construction design and planning, the algorithm is intended for multiple objectives. The study also presents an innovative perspective on this whole process by presenting the qualitative evaluation of the scene based on human evaluation and incorporating changes. The results demonstrate the robustness of the GA framework and also substantiate the utility of the virtual scenarios.

INTRODUCTION

Invariably, today's complex design problems demand coordinated optimization of multiple objectives. The solution is to resourcefully negotiate the different objectives resulting in a judicious compromise. Genetic algorithm (GA) based multiobjective optimization techniques have been successfully applied to a wide range of disciplines in the recent past. Genetic algorithms are heuristic search procedures employed in finding solutions for multiobjective optimization problems. The GA process generates a group of optimal solutions for the particular multiobjective optimization problem, which is known as the Pareto set, with plans that represent a meticulous trade-off (Stewart, Janssen, & van Herwijnen, 2004). For any design optimization, the decision makers are looking for a single satisfactory solution that can finally be implemented. When using genetic algorithms (Goldberg, 1989) for multiobjective design optimization, it is very important to carefully scrutinize the differences among the candidate solutions to obtain a better knowledge of the basic processes and the satisfaction of objectives. The process of choosing one single solution over others entails exhaustive domain knowledge. Typically, many GA-based design optimization procedures make the final choice of the solution (from the Pareto set) based on some 'higher level information' (Seixas, Nunes, Louren, Lobo, & Condado, 2005). However, when it comes to design and planning, it is not possible to implement all the conflicting solutions in the Pareto set (resulting from the GA process). Hence, we offer a virtual reality based visualization to explore and study the alternative solutions. Visualization, as defined by Spence (2007) as the ability "to form a mental model or mental image of something." (p. 5), is a very handy cognitive ability that holds immense potential in the domain of planning and designing (Tufte, 1990). Spence (2007) noted that advances in computer technology have led to a huge increase in the application of information visualization over the past two decades. Visualization models have been built in research disciplines including medicine, education, mining, GIS (Geographical Information Systems), and various other domains to facilitate information comprehension and analysis. The power of visualization models lie in their ability to present data in a form that allows the viewer to 'see' the information in a way more easily interpreted and understood. Elements that need to be considered in construction design and planning include the floor space, structural requirements of the proposed construction, recreational and public amenities (as required), aesthetic concerns, and so on. Providing satisfactory solutions in the face of conflicting demands by multiple stakeholders is a daunting task. Therefore, the proposed framework offers interactive 3D scene visualization to facilitate comparing the alternatives. The GA in this study includes a well-planned selected set of objectives that are explicitly conflicting: maximization of shopping space, maximization of recreational space, and maximization of public service space. Inherently, these three objectives are conflicting in nature as an increase in one space will lead to a decrease in one or both of the others.

The outline for this paper is as follows: Section 2 discusses the process of multiobjective optimization and the various approaches for multiobjective design optimization. Section 3 delineates the GA methodology employed in this study and explicates the research framework and the components. Section 4 elucidates the shopping mall plans and the adaptation of the GA for the floor plans. Section 5 explains the Desktop VR rendering of the plans. Section 6 provides the discussion followed by section 7 that briefly discusses qualitative scene analysis based on human evaluation and subsequently modifying the scene accordingly. Finally, Section 8 presents the conclusion of the study.

MULTIOBJECTIVE OPTIMIZATION IN ENGINEERING DESIGN PROBLEMS

Notwithstanding the remarkable advancements made within the realm of engineering design, owing to the ever-increasing number of factors in any major project, the design exercise has become a complicated process and satisfying all objectives seems to be a daunting and sometimes impossible task. Every design process today is inherently driven by the needs of the consumer and/or the stakeholders and there should be a means to verify if the proposed plan will meet all the demands. It amounts to a colossal waste of time, effort, and money to construct a project and finally realize that it falls short of some objectives initially set out. Consequently, considerable care has to be exercised during the planning and designing phases. Typical design problems consist of a predefined set of decision variables and a particular number (n) of objective functions that need to be maximized or minimized under a given set of constraints. In order for a plan to be considered part of the Pareto set, no other plan, which is superior in all objectives, should be found. In other words, a plan may outdo the Pareto plan in one objective and a different plan may be better in another objective; however, a 'single plan' does not outperform a Pareto plan in all the objectives. From the above discussion it can be seen that plans that do not belong to the Pareto set (non-Pareto plans) are 'dominated', because a Pareto plan that is better (or that which dominates) already exists.

Multiobjective genetic algorithms (MOGA), a family of heuristic methods, overcome the limitations of traditional methods because it is capable of solving the non-linear, non-additive optimization problems without reformulating the problems. With these merits, MOGA has been adopted in a large number of design and planning research projects (Stewart et al., 2004; Balling, Powell, & Saito, 2004). However, because MOGA usually retrieves a large number of optimal design plans, new techniques are needed in order to facilitate spatial decision making, among which visualization plays an important role. In particular, to visually plot the candidate solutions of the design space is an intuitive way to visualize these optimal alternatives.

METHODOLOGY

The study area considered here is the floor space (400 cells) for a shopping and residential mall that is usually divided into zones (various spaces based on usage). These zones are allowed to assume different values. The genetic framework for the region is represented by a 'gene' for every changeable zone. In this study, we use an integer based genetic representation, i.e. each gene is an integer that can assume any value from among the various designs considered in the study. In this example, the zones are coded as follows: Public Service Space is assigned a FL_CODE of 0, Food Court 1, Parking Spaces 2 Convention/Conference area 3, Recreational spaces 4, Public Service Spaces 5, Commercial Space – Supermarkets 6, Commercial Space – IT offices 7, Commercial Space – Other Shopping Spaces 8, Control and Reserved Spaces 9. Therefore, each zone is plotted or mapped to an integer within the range of 0-9, and the integer values of all such zones are linked together, resulting in an integer string (Chandramouli, Huang, & Xue, 2009).

In the beginning (first generation), a random value is assigned by the GA to each gene. The generation size is chosen as 100, corresponding to 100 floor plans. Then, each plan is scrutinized with respect to the three objectives and three constraints. Plans that meet the constraints are deemed as practicable ones. The goal is to produce a land-use map that will ensure maximum values of shopping space, recreational space, and public service space. As the design variables can assume any of 10 integer values, the total set of possible plans is as big as 10n, where n is the number of cells (400). This signifies an enormously discrete search space. Probably only a tool like GA that is robust and efficient is capable of performing multiobjective optimization in such a large search space.

Considerations in GA Formulation

Adequate care has to be taken in the process of formulating the GA. Clear representation of the problem is inevitable for an effective solution. Just as alternative solutions are possible, alternative representations are also possible. When considering floor plans, it is possible to represent the problem in the form of raster or vector spaces. In this case, cells of equal dimensions have been chosen. In other words, the study area has been divided into a grid of rasters. However, it is possible to characterize the same problem using a vector representation similar to that used in Geographical Information Systems (GIS) (This concept is later illustrated using Figure 3a and Figure 3b). In GIS, vectors or polygons are used to denote land parcels whose dimensions are specified using attributes. Also, even when choosing to use a raster-based representation, various options are available. The size of the individual cells is an important factor to be considered. The area can be divided into 20 x 20 cells or 200 x 200 cells or even 2000 x 2000 cells. Several considerations affect this decision including the computing power available for the GA process.

GA Framework

GAs typically consist of the following steps:

- Selection process wherein the individuals for the next generation are chosen
- Manipulation, wherein recombination and mutation are performed using genetic operators

In this study, integer based representation, a common method of encoding used in GAs, has been implemented. The genetic framework for the region is represented by a gene for every changeable zone (Figure 1).

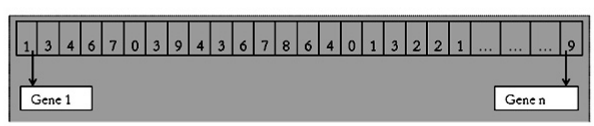


Figure 1. A chromosome structure with integer representation

We use integers because integers are simple and straightforward from the computational perspective. The generation size is chosen as 100, resulting in 100 floor plans at the end of the execution of the first generation. An initial generation is created by a process of random generation in the presence of constraints and the iterations are repeated until a feasible set is obtained. 'Feasible set' refers to plans that satisfy the constraints imposed. During iteration, the plans in a generation are checked individually for satisfaction of the minimum requirements/constraints and those that satisfy these requirements are added to the feasible set and the others are discarded. The procedure is repeated until the initial generation with 100 chromosomes (floor plans) is obtained (Figure 2). After the initial generation is obtained, the selection, recombination, and mutation processes are performed to create the subsequent generation.

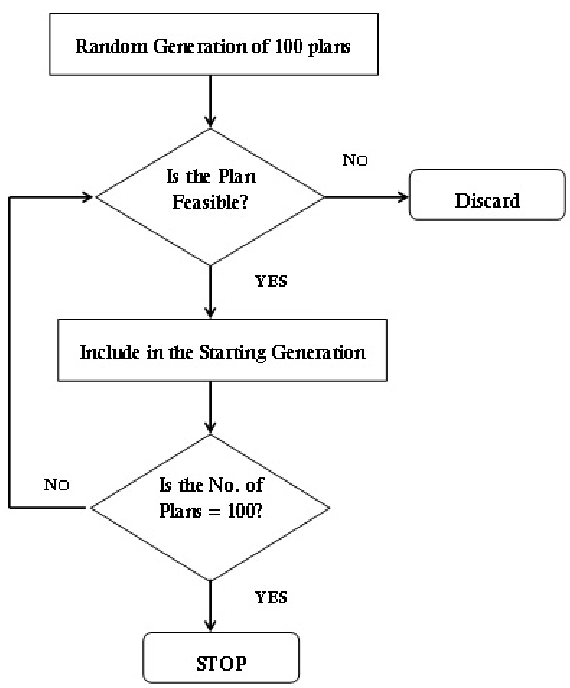


Figure 2. Generation of the 'feasible set'

Selection and Variation

As stated earlier, the GA process consists of two very fundamental operations, namely selection and variation. The selection process is the step whereby the individuals that are 'fit enough' to be passed on to the next generations are chosen. Typically, this process is biased by the fitness of the individuals in such a way that individuals with higher fitness have a great probability to make it to the subsequent generation. The selection process can be stochastic or deterministic; the basic objective is to eliminate the poor quality individuals from the population set. The value of an individual member of the population with respect to the optimization process is represented by a scalar quantity known as 'fitness'. The fitness value is calculated based on the objective functions and constraints. After calculating the fitness values of every individual in the generation, those members with higher fitness values are selected for the subsequent generation. However, not all the members from the present population can be selected for the next generation. This proportion is called the rate of selection or selection rate. For instance, if the selection rate is .2, then out of a population of 100, 20 individuals will be selected for the next generation. Likewise, if n = 100, and x = 0.4, then 40 individuals are obtained by selection and the remaining 60 are generated by the processes of recombination and mutation. One vital consideration during this step is the choice of the number of chromosomes to retain. If there is a considerable number of poor quality chromosomes in the present population, retaining a large number of these chromosomes for the next generation will negatively affect the overall fitness of the generation. On the other hand, if only a minimal number of chromosomes are retained from the present generation to the next generation, this will restrict the number of genes available in the offspring. This step mimics the natural selection process. In the process used in this study, chromosomes with a fitness value below the threshold limit are not considered for the next generation.

Subsequently, recombination, the process of merging the genetic information from two parent chromosomes follows. In the recombination step, a predetermined number of parents are selected and are recombined using crossover operations to create children. In order that the process remains stochastic, a probability rate known as crossover probability is used along with the crossover operator. The crossover point is where the swapping of genes occurs. This point is chosen randomly and it lies between the first and last genes of the chromosomes. At first, one of the two members of the mating pair, called Parent1 provides the genes to the left of the crossover point to the Offspring1 and the second member of the mating pair, Parent2 provides the genes to the right of the crossover point to the Offspring1. Thus, the Offspring1 now contains material from both the parents. Similarly, the second offspring is generated by combining material from Parent1 and Parent2. The genes to the right of the crossover point from Parent1 and that to the left of the crossover point from Parent2 are combined to produce Offspring2. Once the recombination step is over and the crossover operations are complete the generation is full with its complete population of chromosomes. At this stage, random mutations are introduced in the population. Mutation helps the GA process in two ways:

1. Mutation helps prevent premature convergence
2. Mutation aids establishing new traits not present in the original population

Subsequent Generations and Convergence

After the mutation step is completed, the resulting generation is ready for the iterative process. The steps starting from fitness calculation are rerun for the individual chromosomes of the new generation and this generation undergoes the steps of selection, recombination, and mutation as before until the subsequent generation is obtained. The iterative process of the subsequent generations depends on

- Whether specific search criteria have been satisfied or
- Whether a specific number of iterations have been surpassed

Objective Functions and Constraints

In this study, three objectives were considered, which ensure that:

1. The building can accommodate more commercial establishments
2. The recreational spaces are increased,
3. The residents and the shopper get more space for public amenities

Genetic algorithms typically consist of functions or objectives that are to be maximized or minimized during the process of optimization. In this study we wanted to have objectives that are directly and intensely conflicting in terms of area. The first objective was meant to increase the shopping space as typically stakeholders would be interested in enhanced commercial value for higher return on investments. Three index values: CommVal, Recval, and PubVal, are used as objective measures. The objectives are to maximize the commercial value, recreational value, and the amount of public service space. Among the 10 floor space types seen in this study, one particular floor space type needs special consideration. These are the control and reserved spaces, which are set aside for special purposes. Different sets of uses and regulations govern the use of such floor space types and changes, if any, to such areas involve considerable administrative brainstorming. Hence, the floor space types categorized as control and reserved will continue to remain unchanged by the GA process.

The three indices are calculated as follows for the 100 plans in a generation:

for i = 1:100
$Pub_{Val}(i,1) = (Area_{Rec}(i,1))/Sum_{Area}$;
End
Where,
Pub_{Val} = Index for measuring recreational value of a plan,
$Area_{Rec}(i,1)$=Area for recreational spaces in Plan i. &
Sum_{Area} = Total area of all the 400 cells

Similarly, the index values CommVal and PubVal are calculated. The following constraints are imposed on GA:Floor Spaces designated as Emergency Exits and those reserved for Safety purposes are not to be changed, Spaces designated as parking are not to be changed and Specific floor spaces with residential structures are not be changed. In order to ensure these constraints are met, a selected number of cells from among the 400 cells are not allowed to change during the GA process.

Fitness Evaluation

After considering several fitness evaluation procedures, we find the Maximin function (Balling, Taber, Brown, & Day, 1999; Balling et al., 2004) to be very appropriate for GA studies involving problems involving category allocation for floor plans as seen in figure 3.

Val is the current value of corresponding objective, Val_{min} is the least value of all Val values of the plans in the current generation and
Val_{max} is the highest value of all Val values of the plans in the current generation.

Shown above is the normalization of the objectives using a simple and straightforward procedure that involves scaling. Normalization involves finding the maximum as well as the minimum values for each objective for a set of plans in a generation and then re-scaling using the following formula. The number of objectives is 3 in this study. The normalized objectives scores are given using a simple and straightforward technique of linear interpolation. Thus, considering the three objectives concerning Sustainability value of a plan, Economic value, and Recreation value, the normalized scores can be obtained as described above. The plans need to be compared with other plans in the generation to find the fit ones in the generation. As mentioned earlier, for measuring the fitness of the plans, the Maximin fitness function (Balling et al., 1999) is used. The fitness of each plan in a generation is calculated relative to that of the other plans in the same generation. The greater the CommVal, RecVal, and PubVal of a plan, the higher will be the fitness of that plan in comparison with the other plans of the generation. Considering two plans Planj and Plani, Planj is superior to Plani if the indices CommVal, RecVal, and PubVal of Planj are all greater than the corresponding indices of Plani. Planj is superior to Plani if it exceeds it in all the three objectives. if the minimum of the above three differences is greater than 0, then Planj is superior to Plani.. Each plan in a generation must be compared with all the other plans in the generation. If it is to be found whether a Plani is dominated or not, it is compared with all other plans using the aforementioned principle. The fitness of the ith plan is obtained as follows in figure 4 (Balling et al., 1999):

Where,
Range1 = CommValmax – CommValmin
Range2 = RecValmax – RecValmin
Range3 = PubValmax – PubValmin

Range1, Range2, and Range3 represent the scaling factors for the three objectives, for all the plans in a particular generation. However, it should be noted that this value has to be computed during each iteration for every single generation so the maximum and minimum values of each objective varies during each generation. Based on the fitness formula described above, it is possible to identify the Pareto-optimal plans from the fitness values obtained.

GA Implementation

The GA is implemented with the objective of searching and finding a set of plans for the community, which meet the constraints imposed on the GA while maximizing the objectives. Plans that satisfy the constraints are called 'feasible plans'.

$$Plan_j - Plan_i = \frac{Val_j - Val_{min}}{Val_{max} - Val_{min}} - \frac{Val_i - Val_{min}}{Val_{max} - Val_{min}} = \frac{Val_j - Val_i}{Val_{max} - Val_{min}}$$

Figure 3. Maximum function

$$f_i = \left(1 - max_{j \neq i}\left(min\left(\frac{CommVal_j - CommVal_i}{Range_1}\frac{RecVal_j - RecVal_i}{Range_2}\frac{PubVal_j - PubVal_i}{Range_3}\right)\right)\right)^p$$

Figure 4. Fitness formula

The final plans obtained from the GA must be Pareto-optimal with respect to the multiple objectives. Pareto-optimal plans are both 'feasible' and non-dominated. The word non-dominated implies that no other feasible plan in the generation is better than this plan in all objectives. In order to ensure that only plans that satisfy the constraints are included in the very first generation, randomly generated plans are scrutinized to check if they satisfy the aforementioned constraints. Only plans that satisfy the constraints are selected and included in the starting generation. This process is repeated until the starting generation has 100 plans, all of which satisfy the constraints (Table 1). From the starting generation, the second generation is constructed using the GA methodology. The third is generated from the second, the fourth from the third and so on for a total of 100 iterations at the end of which a generation with 100 final, feasible plans results. After mating, mutation is performed to introduce qualities that are not originally present in the parent population. Mutation involves randomly changing a selected number of genes in specific chromosomes obtained from the earlier process. In this study, the mutation probability is chosen as .05. Mutation is typically applied to the offspring generated from the earlier step, subject to the mutation probability. A random number between 0 and 1 is generated for each gene in the two offspring. If the random number is less than the above probability of mutation (.05), then the integer value of the gene is changed to another random value between 0 and 9. The above processes cumulatively represent the complete process of creating a new generation from an earlier generation. This constitutes one sequence of iteration. The whole GA process involves 100 iterations at the end of which the Pareto set containing the Pareto-optimal plans is obtained.

The fitness values of the individual plans in the generation are calculated using the fitness formula described earlier Plans with higher fitness values have higher Pareto-optimality and hence are more 'fit' than the rest of the plans in the generation (the p value chosen here is 15 , Balling et al., 1999, 2004). The plans altogether constitute the Pareto set. Plans belonging to the Pareto set are called non-dominated plans. This is because no other plan exceeds the Pareto plan in all the objectives. A plan may outdo the Pareto plan in one objective and yet another plan may outperform the Pareto plan in another objective; however, no single plan surpasses the Pareto plan in all the objectives. The Pareto set is devoid of the influence of the relative significance of the various objectives. Hence, plans not belonging to the Pareto set are called dominated plans since Pareto plans that surpass these plans have been found. Pareto plans significantly aid the process of decision-making as planners and

Part I. Feasible Set Generation

1. Generate Random Population
2. Check for Constraint Satisfaction
3. Include in Feasible set Upon Satisfying Constraints
4. Repeat Steps 1-3 Till Population Reaches 100
5. Calculate Fitness of Feasible Set(Part II Steps 6-0)
6. Sort
7. Use Sorted Generation as Starting Generation

Part II. GA-Main Loop

1. Initiate Generation Number to 1
2. Select Top 10 Plans from Previous Generation
3. Use Tournament Selection to Select Offspring
4. Perform Mutation
5. Repeat Steps 3and 4 to Get 100 Chromosomes
6. Initialize Indices Matrix for Plans in a Generation
7. Get $Comm_{Val}$, Rec_{Val}, Pub_{Val} for 100 Plans
8. Compute Fitness Values
9. Sort plans based on Fitness
10. Set sorted generation as current generation
11. Repeat steps 1-11 for 100 Generations

Part III. VR-Visualization

1. Select Pareto-plans from Final Generation
2. Identify Scene Elements to Compose Virtual Envt.
3. Render the 3D Elements to Generate Virtual Scene
4. Evaluate Plans & Select 1 Plan for Implementation

Table 1. Algorithm for GA Based 3D Visualization

administrators need not sift through hundreds of thousands of plans; but, they can merely search the Pareto set to find an optimal plan. However, there is still one shortcoming. Decision makers are still confronted with a set of plans from which they have to choose one plan. This process cannot be automated as now the relative significance of the various objectives based on the ultimate development goals should be considered. This is a prototype study that proposes the use of VR-based representation to visualize two plans with high fitness values from the final generation and select one among them as the final plan for implementation.

GENERATING FLOOR PLANS

The study area is divided into 400 cells, each of which has an initial allocation of floor type as elaborated in Table 2. At first look, Figure 5a might not seem to be divided into 400 cells. The study area is classified into zones (or cells) based on their usage (Figure 5a and Table 2). Cells belonging to the same category have been combined together and re-arranged to illustrate a floor plan. The study area could very well be like the one shown in Figure 5b that shows an alternative representation for the same floor area and represents a more detailed and conventional display. In the case of a plan like figure 5b, instead of uniform cells of equal area (or rasters), vectors (or polygons) have to be employed. Otherwise, the methodology described herein holds equally good for any type of representation. For the sake of simplicity and to facilitate a lucid demonstration of our methodology integrating GA with Visualization, we have considered a relatively simple floor space for this study.

Floor Space Type	FL_Code	Gene
Space for Public Utilities	PBL	0
Food Court	FC	1
Parking Spaces	PS	2
Convention Area	CA	3
Recreational Spaces	REC	4
Library	LIB	5
Commercial Space	CS	6
Commercial Space-IT	CSIT	7
Spaces b/w Floor Types	CSS	8
Emergency/Reserved	ERS	9

Table 2. Gene-Floor Types

The plans in the starting generation were generated by a random process in which integer values were allotted to the 100 chromosomes. Each of this is a potential solution to the problem considered in this study, corresponding to the 400 zones in the study area. The set of constraints entail the values of certain design zones to remain invariable. During the starting random generation stage, the plans that did not satisfy these constraints were discarded. From this starting generation, the whole GA process involves 100 iterations resulting in a generation with 100 final, feasible plans. In this study, the mutation probability was chosen as 0.05. On the whole, the average time consumed

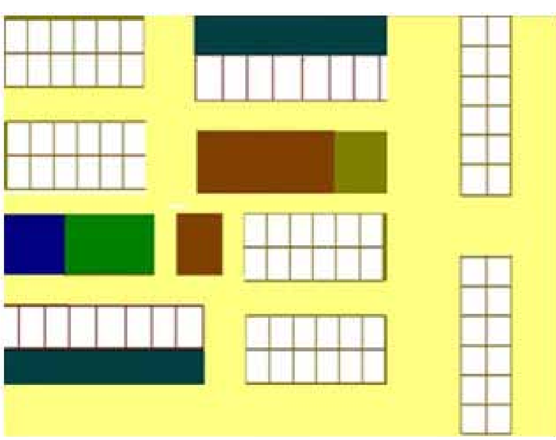


Figure 5a. Study Area – Mall Floor Space

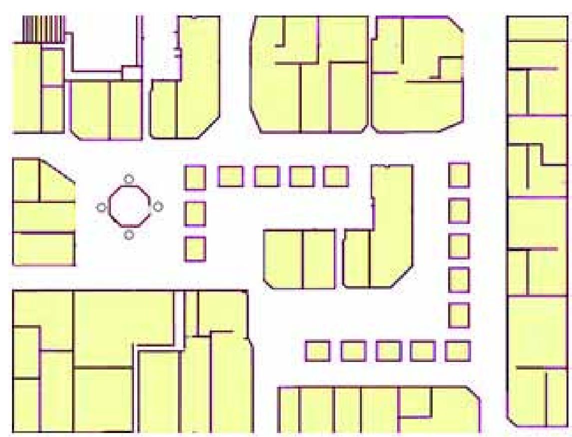


Figure 5b. Alternate Representation - Study Area

for the experiments that were performed on a Pentium-IV machine with 1 GB RAM is 6700 seconds for one execution of 100 generations.

DESKTOP VR RENDERING OF PARETO OPTIMAL DESIGN PLANS

Many GAs generate optimal solutions via iterative optimization procedures. However, the work stops there and then subjective measures are employed to select one plan for implementation. Therefore there is an increasing need for tools or indicators that can efficiently depict design scenes as one comprehensive screenshot rather than a series of non-coherent data layers. Virtual reality visualization can meet such need by facilitating not only presented information, but also enabling seeing and understanding of hidden information among datasets. By using 3D visual scene renderings, planners who are experts in the fields of design planning can identify desirable or undesirable patterns. Aesthetic view quality is of significant importance in design. For instance, a structure blocking the view of a piece of art or some other feature of prominence specifically included to enhance the face value of the shopping mall is undesirable and hence such a design is not judicious. Three-dimensional visualization can greatly facilitate the study of the aesthetic quality of a plan. Furthermore, such visualization tools can be also integrated into public participation systems and allow non-planning experts to get actively involved in the selection process.

```
#VRML V2.0 utf8

DEF Root_Node Transform { children [
    DEF Food_Court Transform {children [
    #.............
    ]}
    DEF Library Transform {children [
    #.............
    ]}
    DEF Public_Utilities Transform {children [
    #.............
    ]}
    DEF Residential Transform {children [
    #.............
    ]}
    DEF Commercial Transform {children [
    #.............
    ]}
    DEF Convention_Area Transform {children [
    #.............
    ]}
    DEF Recreational Transform {children [
    #.............
    ]}

    DEF Emergency_Areas Transform {children [
    #.............
    ]}
    DEF Commercial_IT Transform {children [
    #.............
    ]}
]}
```

Figure 6. Code Snippet Showing Grouping of Scene Objects

Virtual reality has been described in many ways by various researchers. Generally, however, virtual reality can be defined as the application of an artificial environment generated by computer technology to simulate some targeted activity (Connolly, 2005). Virtual environments cover a wide continuum of involvement, including those that are fully immersive for the user - involving multi-sensory input and interactive movement controlled by the user (immersive VR), partially virtual and real environments (augmented VR), or virtual environments fully contained within a two-dimensional computer screen (desktop VR).

In the example presented in this paper, the authors utilize desktop VR to display the results of the Pareto design plans. Regarding the visualization advantage that virtual technologies can provide, Mohler (2000) stated:

> "Virtual reality (VR) technologies provide a unique method for enhancing user visualization of complex three-dimensional objects and environments. By experience and environmental interaction, users can more readily perceive the dimensional relationships of objects typically portrayed through static multiview or pictorial representations. (p. 151)"

A scene-tree construction is used in Virtual Scene Renderings. The root or the parent object consists of whole scene grouped together and all the other components are grouped under this parent object using 'parent-child' relationships (Figure 6). Individual scene elements corresponding to each floor type such as library, convention area, residential, commercial, recreational, public utilities were created from scratch and were positioned according to their corresponding positions as per the Pareto plan obtained in the previous step. For complex objects including multiple parts, various object parts are grouped to form parent objects, leading to complete objects that are once again combined and positioned properly to form bigger objects resulting in the final 3D scene.

Two Pareto-plans with the highest fitness values were selected and visualization plans generated for these. Figure 7 illustrates the various scene elements generated for the virtual scene and Figure 8 shows the complete 3D virtual world composed of all these elements. The individual scene elements are positioned based on their corresponding locations according to the Pareto plan.

Figure 7. VR scene elements corresponding to various categories: Clockwise from Top-Left-Residential, Convention Area, Library, Recreational, Food-court, Public-Amenities

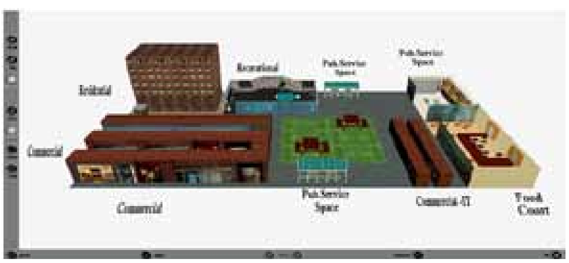


Figure 8. Populating the VR scene with elements corresponding to Pareto Plan

Figure 6 above shows a detailed 3D design corresponding to the Pareto plan. Using such a display, designers and planners can see the potential solution instead of discussing in an abstract manner. Thus, the usefulness of visualization in evaluating CPOPs (Competing Pareto-optimal plans) is evident. The plans can be compared in a very systematic manner by evaluating them based on the objectives considered in this study. Moreover, using various LODs (Level of Detail) and studying the same scene from multiple viewpoints, numerous issues that might not otherwise be obvious can be identified. Subjective features such as scene quality can be studied in a more reliable manner. The same scene can be viewed with varying levels of detail. For instance, when viewing from a distance, the finer details are not obvious. This notion can be used to efficiently model the scene. Based on the viewer's position in a scene, the objects can be rendered accordingly.

DISCUSSION

In this study, interactive and navigable virtual worlds were generated, which can efficiently depict design scenario(s) than a set of paper-based or PC-based 2D data representations. Nevertheless, unless the data is transformed into the 3D format it is not of significant use to planners and decision makers, since interpreting voluminous statistical data is a mammoth and cumbersome task. Visualization aids in understanding the overall scene composition and understanding its function holistically. A closer look at figure 6 shows that some of the originally included floor plans cannot be found. This is because the constraints did not ensure that all the FL_Types were strictly to be represented minimally in the final plan. Hence, after including this in the GA, the plans were regenerated (Figure 9).

Figure 9. Pareto plan including elements such as library and reserved space (Orange)

One prominent advantage of using visualization models is that even a bird's eye view can provide enormous details to the observer. For instance, planners can identify desirable or undesirable patterns using visual scene renderings. The ability to view a scene from innumerable perspectives is an essential functionality to capture the links between the various dimensions of a virtual scene. Scene characteristics that are otherwise incomprehensible become evident when using such advanced 3D visualizations. Furthermore, the software(s) used in this study are Opensource and are web-friendly in the sense that (if the situation demands) hosting them online is extremely straightforward. These worlds can easily be embedded into a HTML/ xHTML file or can be displayed on the popular internet browsers with a plug-in for displaying the 3D worlds.

From the above discussion, it follows that the obvious advantage of using virtual worlds for visualizing the competing Pareto-optimal plans (CPOP) is that patterns (desirable or undesirable) can be easily found (Chandramouli et al., 2009). Using varying LODs and by studying the same scene from multiple viewpoints, numerous aspects that might not be obvious otherwise can be found. Subjective features such as scene quality can be studied in a more reliable manner. From the following figure (Figure 10), the use of visualization to study the same scenario from various viewpoints is evident. Using Anchor nodes (in VRML) annotations or additional information can be added to the virtual worlds – these might include a gamut of information including CAD files, other drawings, MS Project files, etc. Additionally, the External Authoring Interface (EAI) of the virtual scene created above provides a valuable means of extending the scene capabilities beyond what can be used using Anchor nodes available within VRML. The EAI provides an excellent means of enhancing the existing functionalities via Java or JavaScript source code. Such code snippets can be plugged-in to provide advanced functionalities include computational capabilities (where necessary).

Figure 10. Scene Viewed from Varying POV (Points of View)

Another crucial aspect that is facilitated by this integration of desktop VR with GA is the evaluation of the aesthetic view quality. Interior as well exterior design is a prominent issue in engineering planning and design today. The ability to foresee the final renderings in 3D before implementation and being able to provide the stakeholders with a concrete product layout even before the construction can begin is a very valuable asset. Such visual representations serve to rise above the challenges imposed by conventional factors such as scale and viewpoints. The functionalities within the VRML browser plug-ins that enable exploring and studying the same virtual world studied from various orientations is of immense value in scene-analysis (Chandramouli et al., 2009). Furthermore, modern browsers provide excellent features whereby scene elements can be translated, rotated, and manipulated in several other ways.

QUALITATIVE SCENE ANALYSIS BASED ON HUMAN EVALUATION AND SCENE MODIFICATION

A GA greatly facilitates the process of exploring the search space effectively and narrows down the search to a limited area with a very high probability of potential solutions as is described in earlier sections. A GA can be used for imposing constraints and formulating objective functions. However, it may not be possible to include all the elements that "need" to be included in the planning process within a GA. That will necessitate the inclusion in the GA innumerable objective functions and as well as many constraints. Despite numerous objective functions and constraints, it is still possible that some important element were not considered. This might subsequently become evident when using the 3D Scene Visualization. Very simply, some aspects might not be evident unless a structure is in place. Once the structure is in place, some mistake might seem obvious to the observer and might find it implausible that the planners could not have considered that at an earlier stage. Hence, after the design process has passed the GA stage, the planners can still study the visualization and incorporate changes accordingly. This enables incorporating the expertise of the decision makers which may not have been possible in the actual GA process. Some subjective elements pertaining to aesthetic considerations will fall under this category.

CONCLUSION

Today's design problems tend to be multifaceted and the involvement of multiple stakeholders increase the complexity of the number of elements to be considered before finalizing a plan. Even though the search space can be efficiently skimmed using a multiobjective optimization tool such as a genetic algorithms (GA), they still do not provide the decision-makers with a unique solution that can be implemented. The selection of a single solution from the pool of candidate solutions produced at the end of the multiobjective optimization process is by no means trivial. Without exaggeration, it can even be safely stated this might be as critical (if not more) as the actual multiobjective optimization process itself. A solution that has been selected without considering the various perspectives included in the study can seriously undermine the effectiveness of the final solution irrespective of the efficacy of the GA. With these points in consideration, in this study, design planning is formulated as a multi-objective optimization problem, which is solved using genetic algorithms. The study does not stop with merely presenting the results in the form of a Pareto set with a pool of candidate solutions, but visualizes potential solutions using a visualization tool. Visualizing the plans in this manner throws open a plethora of perspectives and simulates the end product that can be visualized, explored, and navigated. This tremendously facilitates the practice of informed decision-making, and in so doing aids the choice of the optimum plan. As mentioned in Section 5 earlier, the online hostability of these scene visualizations greatly enhances the utility of the framework. This not only facilitates the process of obtaining review and feedback from the top-level administrators, but also paves the way for obtaining input from diverse audience owing to the ubiquity of the internet.

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The Understated Value of Freehand Sketching in Technology Education

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Abstract

As education plays such a vital role in economic competitiveness, it is no surprise that the focus for many governments is to invest in educational initiatives. Innovation in pedagogy, refined curriculum and much research into the science of teaching and learning is hoped to promote a knowledge economy. In recent years the Irish education systems have been particularly proactive in the area of technology education. Four new subjects were drafted at Senior Cycle level, all with a common philosophy grounded in design and technology. This clear shift in focus from the traditional craft based subjects to a more creative design-based suite of subjects has brought with it an unprecedented need for continuous professional development.

This paper focuses on the shift in skill set from teaching in a predefined drawing mode to that of a conceptual mode that fosters creativity. As technical sketching is a fundamental building block of all design-based activities, it formed the core of this study. Focusing on the learning process under the descriptors of presage, process and product enabled a linear exploration of an otherwise complex dynamic learning experience.

Although the perception of innate ability restricts the level of application of many teachers in terms of sketching, it proved a valuable attribute as a comparative criterion when selecting contributors. The study included participants that subjectively claimed an average standard of sketching capabilities and a polar group with a prerequisite mindset governed by the phrase "I cannot sketch". All participants completed a purpose designed five-week course of study. The course included much psychomotor skill development; however the significant value of the course content centred on the cognitive development that progressed from knowledge acquisition to synthesis.

The paper concludes by highlighting the value of "Process" based education over the traditional "Product" approach and presents empirical evidence that illustrate enhanced cognitive capabilities of the participants. The use of pre and post intervention data and qualitative commentary validates the suggestion that there is a greater cognitive value to sketching than a completed composition.

INTRODUCTION

The purpose of this study was to investigate if sketching is more than a physical activity which some people excel at and enjoy, while others find difficult and frustrating. It forms part of initial research that is being carried out as part of a greater study at the University of Limerick, which aims to determine how freehand drawing can be taught and applied in technology subjects not only as a means of communication but as a greater cognitive tool.

Technological subjects at pre-university level in Ireland have a broad aim directed towards developing fundamental design skills and aptitudes in pupils. Problem solving, creative thinking and practical skills are integrated into a unique set of subjects with a common philosophy grounded in design. "Designing is a demanding and complex problem solving activity of great economic importance and sketching has an integral part in this" (Schutze, 2003). A central focus is placed on sketching and the influence that technological education has in the development of pupils' ability to sketch. The importance of sketching will be explored under three facets which are cognitive implications, educational significance and the economic benefits.

EDUCATIONAL SIGNIFICANCE

The value of freehand drawing in technology education cannot be underestimated. It has been found that "drawing episodes in design and technology are problematic" and that children are not introduced to the fundamentals of freehand drawing which can help them "develop designerly thinking and behaviours"(Newcomb, 2007). The ability of students differs significantly in the way they learn and process information. The manner in which students respond to their learning environment, approach their studies and their attitudes to different pedagogical styles are something which teachers of Engineering Education must be aware of. They will be much more capable of devising suitable inclusive pedagogical approaches if they have an in-depth understanding of preferential learning styles (Felder, 2005).

It could be argued that sketching is exclusively a communication tool which some people are innately competent at and that it has no other significance. However the syllabus produced by the Department of Education and Science emphasises the value of freehand drawing and the role that it plays in "explaining as well as solving problems" (DOE, 2007). The connection between freehand sketching and the cognitive processing and development of spatial ideas needs to be understood and developed by teachers of engineering education (Gaughran, 1990). Therefore, freehand sketching must become more than a psychomotor skill that is just exploited by the few innately talented pupils in communicating their design composition in technology subjects.

Underlying the ability to manipulate a pencil and sketch a composition are cognitive aptitudes and characteristics which are core to the process. Teachers need to appreciate that appropriate pedagogical approaches required to help pupils "mentally create and edit graphic information" (Contero, Naya, Comany, Saorin, & Conesa, 2005). Once these approaches are applied in technology subjects the benefit will disseminate into other subjects such as mathematics and sciences. This increased awareness of cognitive processing and capacities should result in pedagogic structures that "employ trans-disciplinary knowledge to advance the learning process" (Seery, 2003).

COGNITIVE IMPLICATIONS

The links between freehand drawing, cognitive activity and the development of spatial ideas needs to be developed and encouraged in technology education. In order for this to occur it is important to describe the cognitive aptitudes which are being applied and developed concomitantly during the sketching process. In order for students to develop capability in design and making they must first of all "learn the relationship between sketching and thinking, and how to use sketches to clarify and show details of their design thinking" (Welch, 1999). So not only is it important for educationalists to identify these cognitive aptitudes, it is also important for the pupils themselves to understand how they think themselves.

The global importance of freehand drawing merits investigating whether a link exists between it and spatial ability and whether the product of the two can be developed. Spatial ability is "the mental manipulation of objects and their parts in 2D and 3D space" (Olkun, 2003) and this is governed by the capacity to "perceive the visual world accurately" (Gardner, 1993). Spatial ability is "not innate but can be developed with appropriate tuition" (Gaughran, 1990) and training provided the appropriate resources are used (Olkun, 2003).

Freehand drawing is an invaluable tool in Engineering Graphics education as it encourages the exploration of ideas and concepts and the development of solutions to complex problems in plane and descriptive geometry. It is used to communicate and manipulate information in learning and problem solving activities (Olkun, 2003). The importance of recognising, measuring and developing spatial ability can be undervalued in educational systems due to a mindset fixated on the end product which is terminal examination.

As a result of both pressure to improve overall school performance and excitement and interest about education that could be brain based, many myths and conceptions have grown outside the scientific community with regard to the mind and brain (OECD, 2002). Both cerebral hemispheres of the brain have unique functions in determining the behaviour of people with the right hemisphere generally having non- verbal and spatial characteristics while the left hemisphere generally has verbal, logical and linear characteristics (Edwards, 1989). The developments that are taking place in cognitive neuroscience cannot be underestimated and the application of these findings is required for a reorganisation of the education system (OECD, 2002).

As far back as 1964, it was outlined that procedures used for admittance to educational institutions are heavily weighted to those with superior verbal intelligence (Smith, 1964). Smith argued that a considerable proportion of students with advanced spatial abilities are being prevented from partaking in advanced educational courses where this ability can be nurtured and developed. The Irish education system has taken cognisance of this research and the assessment of project based work in all technology based subjects now forms approximately forty percent of the overall grade. An example of this change in focus is evident in Design and Communication Graphics. Forty percent of marks are weighted towards an assignment which is a design investigation with a conceptual element. It aims to assess elements of design and communication graphics which "cannot be readily assessed through the terminal examination" (DOE, 2007).

ECONOMIC BENEFIT

It has now been established that freehand drawing can help develop pupils' spatial ability, communication skills, problem solving skills and their ability to be creative. These resultant factors have potential to have great implications outside the classroom environment. As education is seen as a driving force in delivering economic benefits to nations, it is appropriate to analyse the advantages that the people who possess a unique cognitive skill set enhanced by freehand sketching have over others.

(Pink, 2006), gives an insight into why countries like Ireland need to move from the knowledge based economy to that of a conceptually driven one. The effects of outsourcing of jobs, automation and abundance are being felt worldwide and countries now need a new type of person to lead. This type of person will have the essential "high concept" aptitude of "symphonic thinking" which is a right brain characteristic (Pink, 2006). According to Pink, this is the ability to synthesise in addition to the ability to analyse; it is the ability to detect broad patterns in addition to specific answers and to see links between things that were never thought possible. The downturn in the global economy indicates that a significant change is needed and this needs to be sparked by the education system.

METHODOLOGY

During the sketching process underlying cognitive activity is undoubtedly occurring contemporaneously and this needs to be qualitatively and quantitatively measured. Future research will focus on developing the key aptitudes which cause this concurrent cognitive activity and how these can be developed and applied in a broader educational context.

Participants

Participants were divided into two separate groups – an investigative focus group (which aimed to classify the cognitive aptitudes of sketchers) and an applied test group (through which a strategy was applied and tested).

The focus group was composed of eighteen people all who classified themselves as having an innate ability to sketch. These were student teachers of technology education at the University of Limerick.

Seven people formed the test group, all of whom were qualified teachers of technology subjects. Five of the participants were undertaking post-graduate research at masters and doctorate level and the remaining two were academics who are lecturing in the department of Manufacturing and Operations Engineering (M&OE). The group was made up of six males and one female with ages ranging from 21-36 with a standard deviation of 5.44.

The test group was composed of two kinds of participant, those who claimed an average standard of sketching and a polar group who claimed they "cannot sketch". All participants were predominantly right handed except for the sole female participant who was left handed.

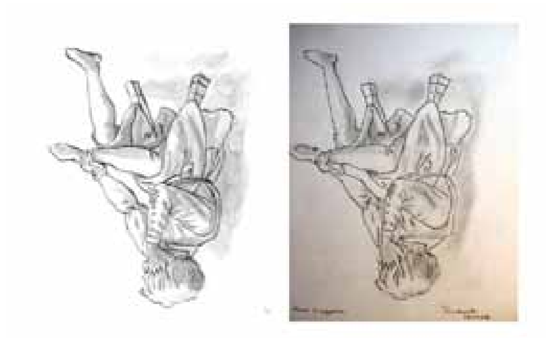
Design

The research was set out in two stages. The first stage aimed to establish the skill set, key aptitudes and characteristics of people with an innate ability to sketch through am investigative focus group. Once these were determined, the second stage involved designing and implementing an approach using the applied test group which aimed to determine if sketching is teachable.

The approach aimed to develop the following aptitudes with a specific purpose:

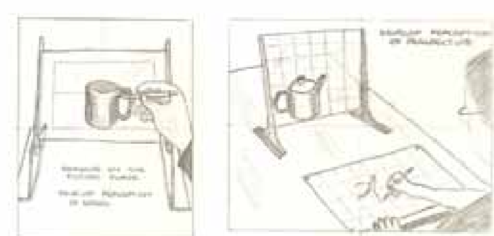
Recognition – A perception proof exercise (figure 1) was devised to encourage the recognition of outline edges of irregular geometries. In order for the geometries to be recognised purely as lines the drawing was inverted so it had no meaning.

Figure 1. Perception Proof Exercise



Enquiry – A perception enhancement exercise was applied so that geometries which are not instantly recognisable could become part of the greater picture. A picture plane device (as shown in figure 2) was used to record intricate detail and this was then transferred to paper.

Figure 2. Exercises using the picture plane



Enlightenment – A space enlightenment exercise was devised so that areas which appear to have no value in a composition suddenly became important. These empty spaces are bounded by edges which are recognised in the previous exercise. A chair was used together with picture plane and a proportion finder in order to draw the given composition.

Application – An amalgamation exercise brought together the aptitudes of recognition, enquiry and enlightenment. This was achieved by drawing a composition which was of interest to the participants using the skills learned in previous exercises. An element was removed from the composition and drawn from memory. The abilities to recognise angles, relationships and light and shadow were developed at this stage.

Synthesis – A conceptual challenge exercise was devised so that the previous skills could be brought together in the composition of a self portrait. A challenge was given where an imaginative element was to be included in the drawing.

Procedure

Three sets of focus groups were formed with the intention of engaging the group in discussions about their early sketching background, preferential learning styles, personal characteristics, influences and their personal approach to sketching. Each focus group session was recorded using dictaphone and results collated. A unique set of characteristics and aptitudes were then identified.

The participant group for the testing were introduced to the unique set of sketching exercises over five evening's with each session lasting three hours. Each exercise aimed to engage and develop a cognitive aptitude which the focus group identified as being necessary for sketching. Questionnaires, critique exercises and group discussions were used throughout the course to evaluate both data and participant opinions.

Findings

Two sets of findings are outlined in this section. The key findings of the investigative focus group are outlined as well as the findings of the applied test group who undertook the exercises to develop the key aptitudes as outlined earlier.

Findings of Focus Group

The following is a summary of collated findings from the focus groups

- All sketched for fun from an early age.
- There was a variance in the environments in which these participants sketched.
- Something always caught their interest before beginning a sketch.
- 64% of participants categorised themselves as being fidgety people.
- 76% didn't notice time when sketching.
- Everybody described themselves as being thinkers with a tendency to notice unusual patterns.
- 52% of participants reported periods of anxiety
- 45% of the group described themselves as being dyslexic
- 43% of participants preferred to draw intricate detail while the 57% appreciated outline edges and relationships

Findings of Applied Test Group

Prior to any instruction, the applied test group were required to draw a self portrait to determine their current ability to sketch. This information was then used as a covariant at the end of the study to determine if any improvement took place. A selection of these drawings is shown in figure 3.

Figure 3. Selection of Pre Instruction drawings

Pre Instruction Drawing

1. 43% of participants expressed their "reasonable satisfaction" with their drawing while 57% "not happy".
2. The consensus was that there was a definite need for improvement.
3. The main part of the face that caused greatest difficulty was the nose, while the proportions between features were easier to communicate accurately.
4. The intricate geometries which make the facial features unique to each individual are very difficult to communicate accurately.

Perception Proof Exercise

This was devised to encourage the recognition of outline edges of irregular geometries. The drawing was inverted in order to reduce the chance of participants relating the shapes to symbols. A selection of participant drawings is shown in figure 4.

Figure 4. Selection of Perception Proof Drawings

Findings

1. All participants expressed a feeling of being "very pleased" with their drawing.
2. They stated that their focus was on proportionality and drawing the picture in parts rather than as a whole.
3. Turning a drawing upside down and dividing it into a number of parts made the participants focus more on shapes and not symbols. They were forced to draw only what could be seen.

Perception Enhancement Exercise

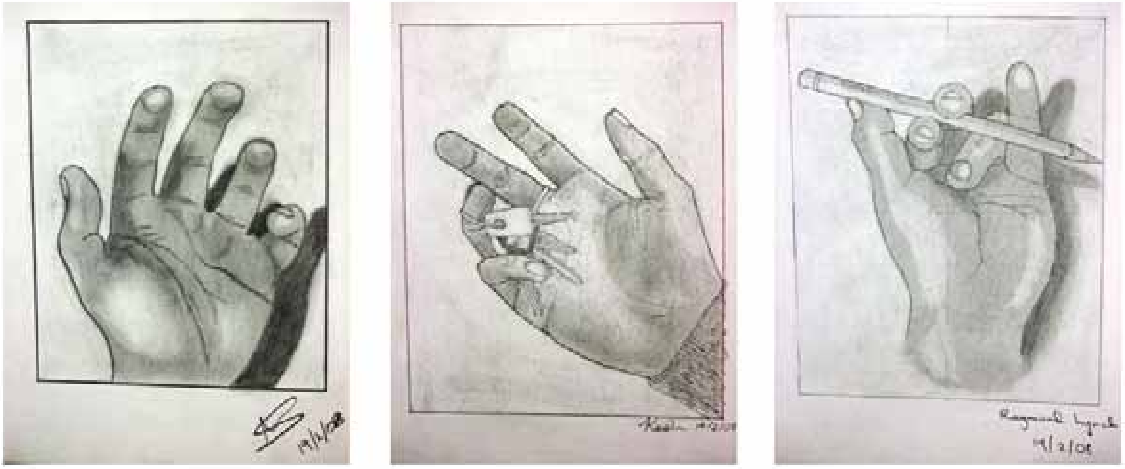
This exercise was applied so that geometries which are not instantly recognisable could become part of the greater picture. A picture plane device (as shown in figure 2) was used to record intricate detail and this was then transferred to paper.

Findings

1. The physical manipulation of the picture plane caused problems
2. The task of drawing edges was difficult for some participants in particular varying the weight and thickness of lines.
3. Participants were able to draw in perfect proportion due to the use of the picture plane and their ability to draw intricate and abstract information was much improved.
4. It was also very interesting to observe the different compositions which people drew, ranging from an open hand with great detail of shadow and shade to an intricate bunch of keys being held in a hand.
5. It is notable that some of the participants expressed surprise in saying "so this is what the picture plane is all about" when using it to determine the composition of their sketch. A selection of these drawings is shown below in Figure 5.

Space Enlightenment Exercise

This exercise was devised so that areas which



Participant A Participant C Participant D

Figure 5. Selection of participants Perception Enhancement Exercises

appear to have no value in a composition suddenly became important. These empty spaces are bounded by edges which are recognised in the previous exercise. A chair was used together with picture plane and a proportion finder in order to draw the given composition. A selection of these drawings is shown in figure 6.

Findings

1. The use of a picture plane to measure the composition of the required solution was used along with a proportion finder to calculate relationships between various elements in the composition.
2. Participants found drawing on the picture plane difficult.
3. Difficulty was expressed in sighting relationships and scaling these to suit the format being drawn upon.
4. 32% of participants found it difficult to see more than one relationship and were overcome by the dexterity in manipulating the equipment being used.

Participant A Participant C

Figure 6. Space Enlightenment exercise

Amalgamation Exercise

This brought together the aptitudes of recognition, enquiry and enlightenment. An element was removed from the composition and drawn from memory. The abilities to recognise angles, relationships and light and shadow were developed at this stage. The element that was removed from the composition is highlighted in figure 7.

Participant A Participant C

Figure 7. Amalgamation Exercise

Findings

1. Participants seemed to have trouble in finding an interesting composition.
2. Intricate detail such as door handles and skirting boards were difficult to measure and communicate.
3. 84% of participants found that they were able to overcome the size of the intricate shapes by relating them to something more regular in the composition.

Conceptual Challenge Exercise

This was devised so that the previous skills could be brought together in the composition of a self portrait. A challenge was given where an imaginative element was to be included in the drawing.

Findings

1. Significant improvement in participants ability was noted all round.
2. 66% of the group expressing a feeling of being "very pleased" with their progress.
3. 34% were "reasonably happy".
4. All participants reported having positive feelings and enjoyment during their experience.
5. Finally, all participants reported a "significant improvement" and their outlook on freehand drawing had totally been changed (see figure 8 below).

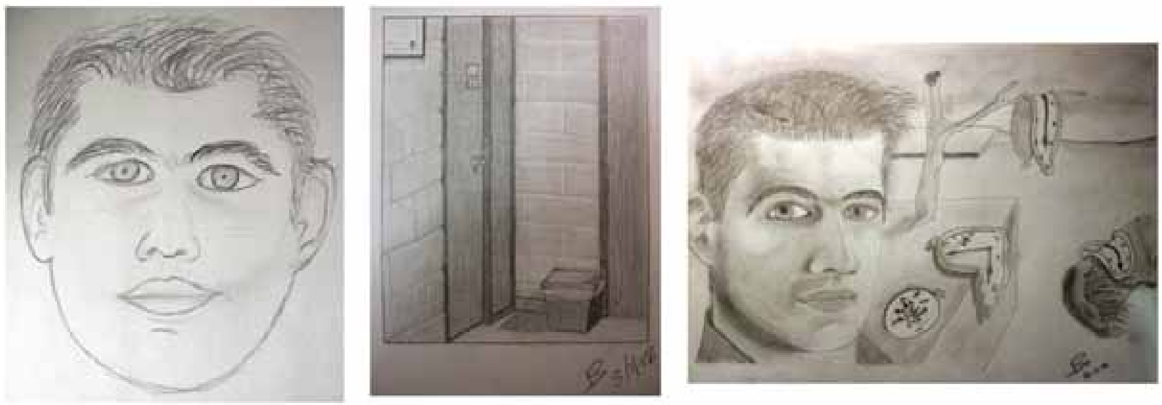
DISCUSSION

In an Irish context, it is notable that pupils who study technical graphics for the first time become so concerned with the dexterity of manipulating the equipment that they fail to understand basic concepts and principles of what they are doing. It can be argued that freehand drawing is just as important in understanding plane and descriptive geometry as well as communication graphics.

Engineering Graphics education with particular reference to freehand sketching has great potential for developing pupil's cognitive, psychomotor and affective domains. The ability to engage in "mental manipulations" and solve problems through freehand sketching will help in the transition from Piaget's "concrete operational" stage to the "formal operational" stage of cognitive development (Snowman, 2006).

It is evident from the results that a significant improvement has occurred in the participant's ability to communicate perceived and conceptual imagery. It is clear that this will have a profound effect on the following areas -

Figure 8. Cognitive challenge exercise



Pre-instruction Exercise Amalgamation Exercise Conceptual Challenge Exercise

Figure 9. Selection of drawings completed by Participant A

- Pupil's visuo-spatial ability and their ability to mentally manipulate spatial problems will be greatly enhanced.
- Pupils will be able to utilise a comprehensive skill set in communicating conceptual design ideas.
- Pupils will be able to analyse mathematical, verbal and written information and represent it graphically.

The work of Participant A is shown in figure 9 below. In relation to engineering graphics the value that this participant has taken from these exercises cannot be underestimated. Some of the key outcomes are as follows –

After completing the course the participant is now able to...

1. Communicate various line-types and line weightings.
2. Identify both regular and irregular geometries in compositions.
3. Analyse proportionality between geometries.
4. Differentiate between shadow and shade and communicate this in rendered drawings.
5. Value the principles and importance of the picture plane when drawing in perspective.
6. Represent perceived 3D imagery on a 2D surface.
7. Create novel designs stemming from external influential factors.

The results of the cognitive challenge exercise prove that the participants were able to produce novel and creative drawings while being influenced by external factors. Participant C, who drew the conceptual challenge exercise in figure 8, was influenced by the famous da Vinci drawing of the Mona Lisa and this is clear from the gestalt of the drawing. These results prove that pupil's ability to communicate design ideas and engage in graphic ideation will improve significantly when exposed to a specific set of cognitive exercises through freehand sketching.

Figure 10. Mona Lisa inspired composition

CONCLUSION

It has now been established that sketching is more than a communication tool and that it has a greater educational significance coupled with cognitive implications which will ultimately be of economic benefit. The philosophy of the Irish education system is to educate individuals so that they may achieve their full potential and contribute to Ireland's social, cultural and economic development. There is a need for increased spending and improved efficiency of education systems in order to meet the "rising demand for more and better education" (OECD, 2008). Therefore the investment that the Irish Government has placed in introducing a new suite of technology subjects is something which must be commended. However, is this monetary investment alone going to advance the pupils who participate in these new subjects at senior cycle? It must be acknowledged that a magnitude of work needs to be done to advance the knowledge and ability of teachers.

Is sketching a teachable skill that can be learned and applied by people who believe they have no innate sketching ability whatsoever? The participants who participated in this study made a significant improvement in their ability to sketch, therefore we can hypothesise that the process used was successful. However, it must be acknowledged that a considerable amount of what was sketched was perceived and was carried out for communication purposes. The research also demonstrates that something deeper is occurring on a cognitive level which involved increased levels of enquiry, recognition of patterns and synthesis between unrelated elements. Further research will reinforce that sketching as a cognitive tool for problem solving, application and understanding can be can be taught and applied successfully.

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Sketching in Design Journals: an Analysis of Visual Representations in the Product Design Process

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Abstract

This paper explores the sketching behavior of designers and the role of sketching in the design process. Observations from a descriptive study of sketches provided in design journals, characterized by a protocol measuring sketching activities, are presented. A distinction is made between journals that are entirely tangible and those that contain some digitally-produced content ("hybrid journals"). The trend between 2004 and 2006 is an increase in both the average number of sketches as well as in the percentage of 3D sketches for hybrid journals. In 2004, tangible journals exhibited a higher average number of sketches over hybrid journals in the user needs and conceptual design stages, but this trend reversed in 2006 where hybrid journals favored more sketches at all design stages. Text was the predominant form of annotation used (ranging from 62-98%), as opposed to dimensions or calculations for both journal types. The industrial design students had significantly more sketches overall and a higher percentage of 3D sketches. They also tended to annotate more in hybrid journals over tangible journals.

INTRODUCTION

Sketching is a critical part of the design process, providing an outlet for developing design concepts, conveying ideas, and recording and sharing relevant design information. However, sketching is a broad categorization, and there are many different ways that designers visually represent their ideas through sketches. Designers employ varying levels of annotation, detail and representation to explore new ideas or develop previous ideas in more detail throughout the design process. Sketches may be done quickly and informally by hand or rendered digitally with a computer-aided drawing tool. Ultimately, designers make sketches to conceptualize a product or concept and represent their ideas.

It is important to understand how sketches contribute to a designer's thought process and externalization of their ideas toward a final product. Creating sketches is a very useful exercise, as the sketches may serve as reminders of previous ideas, assist in current visualizations, highlight future iterations, and more. This paper seeks to understand the sketching behavior of designers in the design process.

The test bed for this research includes design journals collected from two semesters of a graduate-level, multidisciplinary course titled "Managing the New Product Development Process: Design Theory and Methods" taught at UC Berkeley. The protocol used to characterize the design journal sketches builds on that of Song and Agogino (2004). We focus particularly on patterns in visual representations across these metrics:

- Annotation within the sketches
- 2D or 3D representations

RELATED WORK

The importance of drawing to develop and design a finished product is widely recognized (Ullman 1990). Much research has been done to examine how designers record their ideas and thoughts throughout the design process. Goel observes that designers often make rough sketches in the beginning stages, but become more detailed with their drawings in later design stages (1995). McAlpine et al. take a close look at engineers in particular and how they ideate and create in their logbooks (2006). Yang uses design journals as a data source when analyzing sketching behavior in design teams and found correlations with team performance (2007). Oehlberg et al. explore sketching behavior and how it varies with different media types (2009).

Researchers have also worked in detail to characterize and categorize different types of sketches. Ullman examined annotations in sketches, dividing all "support" marks-on-paper into three categories: Text, Calculations, and Dimensions (1990). McGown's "Level of Complexity" measure (1998) and Shah's Idea Categorization (2003) used different approaches to quantify and measures the level of visual or conceptual detail captured in a sketch.

DESCRIPTIVE STUDY

The data used in this research comes from a new product development course taught at UC Berkeley with participating industrial design students from the California College of Arts. This course engages graduate-level students from Engineering, Business, Information, and Science disciplines and senior-level undergraduate Industrial Design students in a rigorous design project to create a marketable product concept within a four-month semester. The students follow a design process that progresses through three design stages: preliminary investigation and user needs studies (Stage 1), concept generation and development (Stage 2), and prototyping and testing (Stage 3). They work in teams of four to six students each, as assigned by faculty. Each team has at least one representative from each disciplinary field and receives coaching from industry consultants and faculty.

The final project can be a physical product, a software interface, or a service. The final deliverables are a working prototype, a presentation, and a poster or demo for a tradeshow booth. Students are expected to keep a design journal throughout the process to record thoughts, ideas, and observations about their project.

This research performs a retroactive analysis of the sketches from two semesters of this design course, Fall 2004 and Fall 2006, totaling 3,470 sketches from 120 journals, representing 31 design teams. Design journals from industrial designers are only available from 2004 and are thus analyzed separately. Sketches are considered to be any visual representation of an idea, regardless of whether it was drawn by hand, photographed or digitally produced. The protocol used to characterize the design sketches is an extension of that used by Song and Agogino (2004). Each of these metrics measures a unique characteristic of the sketches that collectively help illustrate sketching trends during the design process. They are defined as:

- Representation: Two-dimensional (2D), Two-dimensional with multiple viewpoints (2DM, or 2D Multiview), Three-Dimensional (3D), Three-dimensional with multiple viewpoints (3DM, or 3D Multiview).
- Annotation: "support" marks-on-paper, such as text, calculations, and dimensions. Sketches may have no annotations, one type of annotation, or have multiple types of annotations.

Metrics were also added to capture journal and content media. The journal medium can be tangible (paper-based) or digital (computer-based); likewise the content can be tangible (freehand sketched), digital (computer drawn), or mixed (a combination of both tangible and digital content). For this study, "tangible" journals refer to journals that have only tangible content in a tangible journal; "digital" journals contain only digital content in a digital journal; "hybrid" journals are tangible or digital journals that contain both tangible and digital content. As there were minimal digital journals, and the few digital journals contained no sketches, this study reports only on tangible and hybrid journals.

The sketch and journal metrics are compared across the three design stages and over the quantity of sketches to capture individual sketching behavior. Figures 1 and 2 provide examples of sketches from tangible and hybrid journals that demonstrate the aforementioned sketch characteristics.

Figure 1. Example of a page from a hybrid journal, featuring 3D photographs with text annotation.

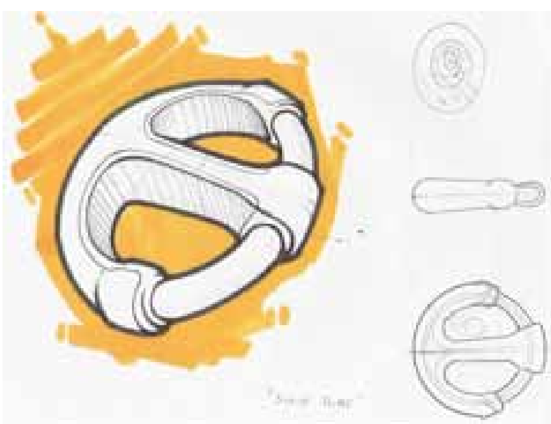

Figure 2. Example of a 3D multiview sketch from a tangible journal, with text annotation.

RESULTS

Table 1 summarizes the average number of sketches per journal produced during a given design phase in 2004 and 2006 for the UC Berkeley students. The results from the design journals of the Industrial Design students from the California College of Arts in 2004 are presented separately in order to isolate trends influenced by the presence of Industrial Design students (Table 2).

	2004		2006	
	Tangible	Hybrid	Tangible	Hybrid
Journal Count				
	29	21	34	24
Average Sketches per Journal				
Stage 1	4.46	2.70	2.24	7.38
Stage 2	16.50	11.90	9.62	15.8
Stage 3	4.93	8.6	4.53	12.45
Overall	25.90	23.28	16.38	35.62

Table 1: Testbed summary, and average sketches per journal at a given design stage. These numbers do not include data from Industrial Designer journals in 2004. Statistically significant results (p<0.05) are highlighted in bold.

	2004	
	Tangible	Hybrid
Journal Count		
	6	5
Average Sketches per Journal		
Stage 1	16.83	7.60
Stage 2	48.83	29.60
Stage 3	24.67	13.40
Total	90.33	50.60

Table 2: Testbed summary, and average sketches per journal at a given design stage, for Industrial Designer journals in 2004. Statistically significant results (p<0.05) are highlighted in bold.

In both 2004 and 2006, designers generated the highest number of sketches during the second design stage (concept generation and development), followed by the third design stage (prototyping), in both hybrid and tangible journals. These results are consistent with those of Song and Agogino (2004), adding that these results are independent of journal medium. ¬

As seen in Table 1 for the Berkeley graduate students, the average number of sketches per journal is higher in stages 1 and 2 for the tangible journals and higher in hybrid journals for stage 3. In 2006 hybrid journals dominated in the average number of sketches over tangible journals in all design stages. Among Industrial Design students, the average number of total sketches per design stage was significantly ($p<0.05$) higher in tangible design journals than in hybrid design journals in all design stages (Table 2).

To consistently compare sketching behavior within a design stage, but across years and mediums with significantly varying average sketch volumes, we shifted our unit of analysis from the total number of sketches in a design stage to the proportion of the overall sketches in a design stage that fit a given sketch characterization. We also filtered out any results that did not contribute sketches in a given design stage. This focuses our analysis more on the proportional content of the design journals as opposed to the relative volume of sketches.

Table 3 presents the results from the analysis for the annotation and representation metrics in 2004 and 2006 for the UC Berkeley students. Table 4 presents the results for 2004 Industrial Design students only.

Text was the predominant form of annotation used (ranging from 62-98%), as opposed to dimensions or calculations in both journal types and across all design stages. It is interesting to note that hybrid journals often contained more sketches with no annotations than tangible journals. This effect was most pronounced and statistically significant in 2006 for design stage 3 where 34.07% of the hybrid sketches had no annotations as compared to 11.93% for the tangible journals. One explanation might be that modern solid modeling and CAD programs allow for embedded annotations in the software for use in analysis, but students may not feel the need to print out these annotations for archiving in their journal.

	2004		2006	
	Tangible	Hybrid	Tangible	Hybrid
Design Stage 1				
Annotation				
Text	91.78%	98.00%	93.10%	81.19%
Dimension	-	-	-	-
Calculation	-	-	-	-
None	8.22%	2.00%	6.41%	18.81%
Multi	-	-	-	-
Representation				
2D	52.98%	84.08%	71.57%	51.57%
2DM	2.88%	3.25%	-	-
3D	44.15%	11.42%	26.09%	48.11%
3DM	-	1.25%	-	0.32%
Design Stage 2				
Annotation				
Text	85.44%	79.65%	86.89%	81.07%
Dimension	5.40%	3.68%	-	-
Calculation	-	-	-	-
None	9.03%	16.45%	10.28%	16.55%
Multi	15.34%	8.75%	2.83%	-
Representation				
2D	63.66%	74.74%	51.68%	57.84%
2DM	2.82%	2.77%	0.70%	0.39%
3D	32.67%	20.81%	47.17%	41.77%
3DM	0.85%	1.32%	0.22%	-
Design Stage 3				
Annotation				
Text	73.26%	74.04%	84.20%	62.41%
Dimension	5.97%	8.36%	1.21%	0.59%
Calculation	-	-	-	-
None	17.79%	18.47%	11.93%	34.07%
Multi	4.06%	4.75%	2.67%	2.92%
Representation				
2D	77.61%	63.03%	42.45%	42.59%
2DM	3.32%	0.93%	-	0.82%
3D	19.07%	34.48%	56.96%	52.50%
3DM	-	1.97%	0.59%	2.27%

Table 3: Summary of results from the analysis of the proportionality of metrics at a given design stage, within the set of journals of a given medium that contributed sketches to that design stage. Statistically significant results ($p<0.05$) are highlighted in bold. These results do not include the 2004 Industrial Designers.

	2004	
	Tangible	Hybrid
Design Stage 1		
Annotation		
Text	62.28%	72.28%
Dimension	-	-
Calculation	-	-
None	37.72%	27.72%
Multi	-	-
Representation		
2D	54.90%	61.13%
2DM	1.55%	-
3D	43.54%	37.90%
3DM	-	0.96%
Design Stage 2		
Annotation		
Text	22.36%	65.97%
Dimension	0.21%	-
Calculation	-	-
None	67.03%	33.36%
Multi	-	-
Representation		
2D	37.03%	15.49%
2DM	7.86%	1.66%
3D	54.94%	81.0%
3DM	0.15%	11.84%
Design Stage 3		
Annotation		
Text	18.77%	55.03%
Dimension	0.98%	2.08%
Calculation	-	-
None	61.11%	40.06%
Multi	-	4.35%
Representation		
2D	47.00%	63.03%
2DM	4.41%	2.27%
3D	46.52%	36.42%
3DM	2.04%	0.69%

Table 4: Summary of results from the analysis of the proportionality of metrics at a given design stage, within the set of journals of a given medium that contributed sketches to that design stage, isolating the effect of the Industrial Designers in 2004. Statistically significant results ($p<0.05$) are highlighted in bold.

The trend between 2004 and 2006 is an increase in the percentage of 3D sketches for tangible journals in design stages 2 and 3 and in all design stages for hybrid journals.

In 2004, the tangible design journal users had a significantly ($p<0.05$) higher average percentage of 3D sketches than their hybrid journal counterparts in design stages 1 and 2, while the hybrid journal dominated the 3D sketches in stage 3. This trend reversed in 2006 where the hybrid journals had the higher number of 3D sketches in design stage 1 and a relatively equal balance with tangible journals in design stages 2 and 3.

The 2004 Industrial Design students (Table 4) had a much higher percentage of 3D drawings in all design stages than the students from other disciplines (Table 3). Among the Industrial Design students the hybrid journals had a higher percentage of both 3D and annotated sketches than the tangible journals.

DISCUSSION

From the descriptive analyses of designers' journals and their sketching behavior, the following overall observations are presented.

- Design journal use varies across design phases.

Although designers are using their journals to support all steps of the design process, these journals are not being used in the same manner at each stage. Song and Agogino (2004) demonstrate that factors including generation vary from design stage to design stage. In this study, the increase of sketches in the second design stage was confirmed. Other factors also produced variable results over time, such as representation and annotation.

- Industrial designers' sketching behavior is dramatically different from that of other disciplines.

The average number of sketches across all design stages for the industrial designers was 90.33 and 50.60, respectively for tangible and hybrid journals. The corresponding numbers for the journals by students in the other disciplines (Engineering, Business, Information, Science) were 25.90 and 23.28. The industrial designers also tended to draw more of their sketches in 3D. This trend was most pronounced in the conceptual design stage 2 with hybrid journal users (81.0% versus 20.8%). This stark contrast raises the question of whether engineering students would benefit from industrial design pedagogies and approaches to sketching.

- Increased technological fluency is changing the way designers sketch and visualize ideas.

Comparing the 2004 and 2006 results illustrates the increasing pervasiveness of digital technology within our tangible information worlds; not only have designers been shifting to hybrid journals instead of exclusively tangible journals over the past few years (Oehlberg et. al, 2009), but the 2006 hybrid journal users are also representing a higher percentage of their ideas in three-dimensions instead of two. We hypothesize that this higher-degree of representation is due to the increasing use and influence of digital tools such as CAD, digital cameras and photography, and access to information and graphics over the internet.

CONCLUSION

This paper has explored variations in content in the practice of design journals. A comprehensive descriptive study of student journals in multifunctional graduate design teams over two semesters was performed. The results highlight trends and affordances associated with the representation and annotation sketch characteristics among tangible and hybrid journals. This analysis provides a basis for future research in developing design journals to support efficient ideation and realization of concepts in the product design process.

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