Abstract

Suh’s Axiomatic Design (AD) methodology has been employed to solve technical problems in a variety of disciplines. One area of interest is the use of this methodology in creative fields such as interactive art. In this paper, the authors propose and implement the use of AD in this manner. We call this approach “Creative AD”. Creative AD was deployed in visual art project courses at the Iceland Academy of the Arts in collaboration with Reykjavík University’s Science and Engineering Department to develop “Interactive electro-mechanical art”. The first iteration of innovative and multi-disciplinary works were selected to be displayed at Hreindýraland Festival 2011 in Egilsstaðir, Iceland.

1. Introduction

Axiomatic Design (AD) is a methodology for matching customer needs (or attributes) to the functional requirements then design parameters for an instance of a solution [1,2]. Traditionally this has been applied directly to manufacturing or product design problems such as designing a rocket parachute release system [3]. However, this methodology is general enough that it can be employed on any system that needs to fulfill a set of “needs”. This includes ROI on financial systems [4], airport special-needs assistance [5], and even getting people to pay their taxes [6]. Using AD in more creative endeavors has even been explored in television recording [7]. Foley et al. have explored using Suh’s Complexity consideration from AD for puzzles, physical security, unique identification, and sabotage [8].

The focus on needs can easily be combined with the Benefvides’ design quality definition heuristic [9] in Equation 1

\[
\text{quality} = \frac{\text{Satisfaction of Needs}}{\text{Resources consumed}} \quad (1)
\]

for a general evaluation of any kind of design. The challenge is how to define appropriate and clear needs in creative fields where there is often a resistance to being “pinned down”. Pushing the question further: how do you generate needs that can be agreed upon when the experts do not have a common terminology to begin with? The authors explored this question in a pilot project between “VT HUN1013 Hönnun (Design)” at Reykjavik University and “GAV 1013M Gagnvirkni (Interactivity)” at Iceland Academy of the Arts [10]. This project later became “T-428-EMIR, Gagnvirk rafvélræn list (Electromechanical Interactive Art)” This venue is an excellent avenue for asking such a question because it is inherently multi-discipline. Traditional works can be completed by a single artist skilled in a single field. These works inherently require collaboration between technical implementer and artistic conceptualist, who do not necessarily have a common language. We found a common language based upon Axiomatic Design.

Nomenclature

| AD | Axiomatic Design |
| CN | Customer Need |
| FR | Functional Requirement |
| FŘ | Feeling/Experience Requirement |
| DP | Design Parameter |

1.1. Axiomatic Design

Axiomatic Design was created to turn design from an art into a science. Dr. Nam Suh developed this approach to try to find common elements between good designs and contrast them to bad designs. His investigation led to focusing on the relationship between needs and their satisfaction, encapsulated
in two Axioms. The goal of any design is to reach the highest quality design solution satisfying needs while minimizing resources utilized as mentioned in Equation 1 [9,11]. This result of an Axiomatic Design process is a structured description of how customer needs are systematically satisfied\(^1\) that fulfills all the needs of the customer\(^2\), in the fewest iterations [12].

In Suh’s own words, “Axiomatic Design defines design as the mapping process from the functional domain to the physical domain, with the aim of satisfying the functional requirements specified by the designer” [1, page 26]. Once a proper set of need-driven requirements are generated, designers search for appropriate Design Parameters (DPs) which are able to meet the FRs. Each FR and DP are considered in a transfer matrix for first-order effects which would couple them together as shown in Equation 2 [1].

AD’s first axiom specifies that coupling between FRs must be minimized. If the matrix only has non-zero elements on the diagonal, it is “uncoupled” and easily optimized. In addition, elements can be easily changed due to changing needs or availability. If the matrix is triangular, it is “decoupled” and can be solved if the DPs are set in the right order i.e. “path-dependent”. Any other configuration of non-zero elements is “coupled”, which makes optimization very difficult. Changing one element affects many, so they must all be taken into account.

AD’s second axiom then suggests that the best solutions are the ones with “minimal information” in the information theory context. Simply put, systems that can most overlap the design and operating ranges have highest probability of success [1].

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
\vdots \\
FR_n
\end{bmatrix} = \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
\vdots & \vdots & \vdots \\
A_{m1} & A_{m2} & A_{m3}
\end{bmatrix} \begin{bmatrix}
DP_1 \\
DP_2 \\
\vdots \\
DP_m
\end{bmatrix}
\]

(2)

The initial question for applying AD in creative contexts such as art becomes: “What would the needs of an art work be?” To answer this, we must consider the context in which the methodology will be applied, particularly the backgrounds of the participants.

1.2. Course Conception

“Hönnun”, an Applied Engineering track class, traditionally focused on designing mechanical projects such as a pump flange or hay bale loading and transport. The RU instructor’s experiences have shown that the biggest design challenges are often not in the technical elements, but instead the communication and integration. In particular, interfacing with a customer and extracting concrete, consistent, and relevant needs is often a significant challenge. The students needed to experience the discomfort of working with a customer who has a completely different set of conditions and may not be able to express their needs effectively [17]. Through this experience, they would see how finding a common communication method was critical.

The visual arts students would take the initial role of “customers” to the engineering students to build art making use of technology and science. The engineering students had mixed reactions to this proposal, but they were interested in the experience especially when explained as a product design exercise.

“Gagnvirkni”, a Visual Arts track class in the Icelandic Academy of Arts, traditionally focused on making interactive art. Through use of technology, a space is created for the audience to become involved in the work’s display. To work with engineering students was exciting for the art students; they saw the possibility to create works that would otherwise be out of their reach.

To minimize cost and maximize accessibility, we standardized on Arduino micro-controllers as our control system of choice. The open-source hardware and software community provided excellent starting tools and examples for unfamiliar with micro-controller technology. The history of this system is significant as it was developed to enable students to develop “interactive design” also known as “physical computing” [18].

With the logistics in place, both disciplines were ready to explore the concept of interactivity. As with any design, it always begins with a need which leads to a base requirement:

\[ CN_0 \]

Get the audience involved in the artwork.

\[ FR_0 \]

Invite the audience into interacting with the artwork.

1.3. Interactivity

The needs are particularly evident in early works created by artists such as John Cage, a pioneer in interactive art. In his seminal work 4’33” first performed in August 1952, he did not employ complicated technology to demonstrate the core concept of interactivity. However, he did create a defined experience. The piece began as follows: a grand piano sat on a stage. David Tudor (a pianist) arrived, placed the hand-written score by Cage on the piano. He then played four minutes and thirty-three seconds of silence, using a stopwatch to keep track of the timing and turning the pages according to Cage’s specialized notation. The sounds of the environment including the audience composed the work. In his 1965 work “Variations V”, he went even further breaking the traditional artistic boundaries by introducing the audience directly into the performance space [19].

In 1966 E.A.T (Experiments in Art and Technology) was founded by Swedish engineer Billy Klüver together with Robert Rauschenbert, Fred Waldhauer, and Robert Whiteinan. The group was focused on creating collaboration between artist and engineers in interdisciplinary technology-based art projects. The culminating project by this group was “Pepsi Pavilion” for the Expo ’90 in Osaka, Japan [20].

As the class was an experiment, the drive of the teachers were the curiosity for the outcome more than following the steps of artists that could be classed as working with AD. Looking back at the students works, there are clear influences from local artists such as the Vasilikas. Their work has always been pushing the boundaries of technology by combining engineering methods and creation. “Violin power” of Steina Vasilikas adapted a MIDI violin to algorithmically control a video output [13]. The installation “Brotherhood” by Woody Vasilikas [14] consisted of a variety of acoustic and visual output

\(^1\)be it a system, an artifact, or a process

\(^2\)that the designer has turned into Functional Requirements (FRs)
modules affected by sensors. Both are clear inspirations as will be shown in Section 3.

Artists working with big scale enduring structures are often working together with engineers, especially if they want to endure the harsh Icelandic climate. The structured design methodologies similar to AD are clearly employed in works such as the water sculpture “Frissa” by the Icelandic artist Rúrulf. This challenging engineering project was completed in 1995 and consists of computer controlled fountains permanently installed at the Reykjavík Botanical Garden [15].

It does not need to be a big scale project for artist to collaborate with technical experts on a functional artwork. An good example of that is “little sun”, a solar led lamp by artist Olafur Eliasson and engineer Frederik Ottesen [16]. These are only few of the many artists that have created interactive artwork requiring a structured approach to collaboration such as AD.

1.4. Motivating Cultural Differences

The artist process for developing a complex interactive work is often defined by the programming capability of that artist. The artist often needs to hire consultants if they want to create complicated artwork. Acquiring sufficient funding for these integrated works is difficult. It is believed that this issue is the main deterrent to an artist’s consideration of integrating technology into their work.

In contrast, delegation is considered standard practice in engineering. On a larger project, a domain-specific engineering student is unlikely to work on elements outside of his area of study. This is to maximize efficiency and chance of success. As part of design courses, students are taught to know their boundaries and be intelligently able to delegate elements when possible. This also allows engineers to focus on becoming extremely capable at a smaller subset of skills, greatly increasing depth.

These contrasting views of collaboration may be heavily influenced by the future career path of each group. In the modern day, engineers rarely work alone on anything. Artists are generally self-employed solo performers (except in music or interactive art). There is a great opportunity for both groups in such an exercise due to the differences. Engineers improve their ability to work outside their comfort zones. Artists get insight into a more structured collaboration model.

Merely mixing the groups together is not sufficient for collaboration. A framework is needed for efficient communication and project management.

As art forms are changing with development of technology and artists are working more and more on cross-discipline works the traditional art teaching at the Iceland Academy of the Arts also needs to undergo change in order to prepare the art student for more structural approach and communication. The result of this collaboration was unfortunately seen as a threat to traditional art practice in the visual art department. The music department saw interest in this concept and two more iterations were made with a combination of engineering, computer science, music and visual art students. Sadly, due to dropping student registration and a change of management at IAA, this collaboration ended after those iterations. Soon after, a new collaboration was started by RU computer science with the IAA design department to develop innovative video games.

<table>
<thead>
<tr>
<th>Table 1: FR and JFR best practices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FR</strong></td>
</tr>
<tr>
<td>action/transforming verb</td>
</tr>
<tr>
<td>verifiable</td>
</tr>
<tr>
<td>collectively exhaustive, mutually exclusive (CEME)</td>
</tr>
</tbody>
</table>

2. Creative Axiomatic Design

The creative process is often described as controlled chaos. This is certainly true on visual arts instruction where the goal is to inspire students to take risks and do completely new concepts. We wanted to make order out of the chaos without interfering with creative thought. The process of idea conception and implementation was modeled after traditional product design needs analysis[21, pp. 36–50]

1. Define the scope of the effort
2. Gather raw data from customers
3. Interpret raw data in terms of customer needs
4. Organize the needs into a hierarchy
5. Establish the relative importance of the needs
6. Reflect on the results and the process

Brainstorming sessions generated many ideas and were used to match artists and engineers to projects of their interests. The scope of each concept was explored during group discussion sessions. These ideas were filtered down to a single concept that was then used to generate Axiomatic Design FR and DP specifications. These specifications were used to ensure that considered design elements meet the needs of the design. At this point, the instructors discovered a significant unexpected obstacle: creating formal requirements make artists uncomfortable while making engineers able to work. We needed a compromise, so we attacked the problem by focusing on “needs” at a top level using “concepts” to explore3. This worked initially, but lacked focus and did not prove the implementer with enough direction.

The instructors re-examined FR best practices in the product context as shown in the left column of Table 1: We then realized that the key component was the “verb” which would map to “feeling” in the context of creative arts.

When defining an interactive piece, during the creative process it is important to think about “how to reach the viewer, to capture the viewer’s interest and to deepen the viewer’s insight into the content of the work” [23]. Artist Haldór Úlfarsson’s gave an inspiring presentation on interactive Finnish art at the beginning. He made the statement “Art is something that makes you feel.” This statement became our inspiration: the teams needed to think about the impact on the viewer in terms of feeling. They must invite and focus their attention on the elements

3The authors discovered that this was a simplified form of C-K theory as described in [22]
that are important such that the patron is seduced into the interaction. An interactive art piece’s evolution only comes about when the viewer transitions into a user [23].

We restyled the FRs to be about “definition of experiences” and “feelings” which became Feeling Requirements (FR). This approach resonated with the students and they were able to use them to discuss the elements and progress of their works in a way that was accepted by both disciplines. DPs became about the instantiation of the interactive piece, which is what the engineering students focused on. For FR, best practices are shown in the right column of Table 1.

We now consider how these changes relate to the standard AD tools of design matrices and Axioms.

In the case of the design matrix, the process and information encoded remains relatively unchanged. Each FR is examined for how many DPs are affected by it at a first order. The question is asked for each pair “Would changing this tool or technique significantly change the experience?”

An interactive artwork that has less FR coupling is likely to be higher quality than one that is not, as the Independence Axiom suggests. An uncoupled artwork is best due to the improved chances that it will be completed on time [24] and allowances for the artist to choose between different DPs to find which one is most appropriate. If choosing a DP affects multiple FRs, then it is harder to make sure that the artistic quality of the work is preserved as that implementation is developed. In addition, as previously mentioned, cost constraints are ever present in interactive art. This means that the DP selection has more options if the system is less coupled.

The Information Axiom takes a subtly different flavor when applied to art pieces. In product design, this axiom focuses on ensuring that the system always works or meets the design range (who it should impact) and the operating range (who it does impact) are maximally aligned.

The Creative Axiomatic Design concept worked well during the collaboration, as shown in the student’s works.

3. Individual Works

Posters for each of these works with a more detailed description are available by contacting the authors.

3.1. Project 1: “Clinging Tree” by Eiríkur Rúnarsson, Erla Axelsdóttir, Jón Sverrisson

<table>
<thead>
<tr>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>joyful</td>
</tr>
<tr>
<td>2</td>
<td>playful</td>
</tr>
<tr>
<td>3</td>
<td>inviting</td>
</tr>
</tbody>
</table>

\[
\{ FR_1 \} = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \quad \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}
\]

\[
\text{FR} \begin{bmatrix} \{ FR_1 \} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \]
(3)

Customer Need was defined as “To bring joy and music to people.” A variety of household items were attached to a welded metal “tree”. These items were hit by solenoids controlled by an Arduino Mega micro-controller connected to a high-power relay network. The micro-controller was given signals from a set of switches hidden under a colorful rug [10]. Depending upon the switch being activated, the solenoid would play a given “instrument” once or multiple times. The design matrix (Eq. 3) was uncoupled because the trigger mechanism and the sound generation mechanism could have easily been exchanged for other elements and still fit the original concept. As one might expect, this was one of the most popular works, especially with children.

The FR and DP of the “Clinging Tree” project could easily be changed to give a scary feeling for instance in stead of a happy one. This could be simply accomplished by changing the components creating the sounds with components such as the scissors from the project “Behind Those Wall Stories” (Section 3.3) that surprise the spectator and possibly injure if they get too close.

3.2. Project 2: “Behind Dynamix” by Sunneva Weisshappel, Hjálmar Pórvaldsson, and Rúnar Viggósson

<table>
<thead>
<tr>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>present at performance</td>
</tr>
<tr>
<td>2</td>
<td>mapping sound</td>
</tr>
<tr>
<td></td>
<td>changes in video</td>
</tr>
</tbody>
</table>

\[
\text{FR} \begin{bmatrix} \{ FR_1 \} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \]
(4)

The goal of this performance piece was to create an instrument with interesting sounds that would complement and control a series of video streams: a quadruped robot BigDog demonstrating mobility under significant challenge, laryngoscope inspection of a participant vocal chords seeming to talk, and a black and white movie on the events at a circus sideshow telling a chilling story. The instrument had four bass strings connected to a set of guitar pickups and finally to a resonance chamber made from an oil drum. The output of the pickups were fed into a computer running MaxMSP to fade between the video streams depending upon the note played. The complete performance had the performer and a partner in full white-face clown and tutu sing while playing the instrument with cello bow and hammer [10]. As shown in Eq. 4, it was heavily coupled due to the customer being very focused on how the instrument would be used in the performance. This was one of the most difficult pieces to get working and the reliability was always in question. Surprisingly enough to the engineers, the artist did not mind that the control was inconsistent as long as it was “interesting”. 

\[ \text{they don’t want to be “pinned down”} \]
3.3. Project 3: “Behind Those Wall Stories” by Fannar Andrason, Katrin Eyjólfsdóttir, Kristián Orri Magnússon, and Nina Fríge

<table>
<thead>
<tr>
<th>( T_F )</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fear</td>
<td>unpleasant surprises</td>
</tr>
<tr>
<td>1.1 visual fear</td>
<td>scary looking robots painted black</td>
</tr>
<tr>
<td>1.2 auditory fear</td>
<td>loud noises</td>
</tr>
<tr>
<td>1.3 physical fear</td>
<td>robot rotating with scissors</td>
</tr>
<tr>
<td>2 intimate aggression</td>
<td>interaction related to viewer distance</td>
</tr>
<tr>
<td>2.1 intimacy</td>
<td>eye animates</td>
</tr>
<tr>
<td>2.2 aggression</td>
<td>distance sensor increases activity when distance is shorter</td>
</tr>
<tr>
<td>3 cut (un)-reality</td>
<td>robot cutting bubbles</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
T_{F_1} \\
T_{F_1,1} \\
T_{F_2,1} \\
T_{F_1,2} \\
T_{F_2,2} \\
T_{F_1,3} \\
T_{F_2,3} \\
T_F \end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 & 0 & X & DP_1 \\
X & 0 & 0 & 0 & 0 & 0 & DP_{1,1} \\
0 & X & 0 & 0 & 0 & 0 & DP_{1,2} \\
0 & 0 & X & 0 & 0 & X & DP_{1,3} \\
0 & 0 & 0 & X & 0 & X & DP_{2,1} \\
0 & 0 & 0 & 0 & X & 0 & DP_{2,2} \\
0 & 0 & 0 & 0 & 0 & 0 & X & DP_3 \\
\end{bmatrix}
\]

\( (5) \)

The artist’s concept \( T_F \) was “An unpleasant argument in a family dining room” As the audience approached the entirely black piece in a darkened room, they would notice an eye on a large round table surrounded by angry, spiked, chairs. As they drew closer, elements of the piece would come alive: the eye would begin sparkling, a tentacled monster hidden in the corner would begin blowing bubbles, and finally an Arthur Ganson inspired robot with scissors began attacking the bubbles.\(^5\)

The installation was controlled by a Zelio PLC (Programmable Logic Controller) industrial controller with distance information from a MaxBotix ultrasonic sensor. The PLC was also connected to a computer with MaxMSP to control the eye [10]. This system was decoupled (Eq 5) due to the artist’s insistence on making a “dangerous” robot that would cut at things wildly. This proved to be one of the more time-consuming elements in the project but with careful planning, the engineers were able to construct it. The rest of the elements were independent and easily worked on in parallel.

The \( T_F \) and DP can easily be changed in this piece for just as good quality work. The black color scheme of the work adds to a mysterious or scary feeling but if changed to bright colored elements, they would have contributed to a happy feeling. Replacing the scissors with a softer element complementing the newly bright bubble machine would complete the conversion to a joyous interactive piece. This new piece could have just as much artistic merit even though the implementation would be quite different.

\(^5\)and people if you get too close

\(^6\)In an earlier version, the chairs would also begin slamming into the table as if there were a poltergeist.

3.4. Project 4: “Forest” by Lilah Leopold, Benedikt Bergmann Arason and Sveinn Haukur Albertsson

<table>
<thead>
<tr>
<th>( T_F )</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 growing</td>
<td>moving plant-like organic fabric structures</td>
</tr>
<tr>
<td>1.1 swaying</td>
<td>leaf blowing in wind</td>
</tr>
<tr>
<td>1.2 unfurling</td>
<td>sail-flower opening</td>
</tr>
<tr>
<td>1.2 emerging</td>
<td>mushroom growing upwards</td>
</tr>
<tr>
<td>2 restful</td>
<td>pressure sensors under seats</td>
</tr>
</tbody>
</table>

Their vision was a dynamic forest with plants that would unexpectedly but calmly move as the viewers entered the space and stayed for a while. The goal was to get the viewers to sit down and also to realize that by sitting down they triggered an action of one of the sculptural components. By this the students hoped that the participant would feel like being a part of a growing changing environment in which their actions did cause reactions. The final version included a video loop of a lakeside shore projected on the canvas of “plants”. Three plants were developed (Fig. 1), each demonstrating a different kind of industrial control model using a single Arduino UNO. LEAF instantiated as a slowly swaying person-sized leaf, using a continuous servo which reversed upon a limit switch being closed. SAIL, one of the earliest concepts unfurled a single-petal flower and also to realize that by sitting down they triggered an unexpected but calmly move as the viewers entered the space.

4. Conclusion

At the end of the course, we presented the seven interactive art projects at IAA under the title “Emerging and Imposing Spaces” ("Vaxandi og upþpréngandi rými") on March 1–6 2011. We were then invited to show a selection of projects to Heimirðarlind Festival 2011 [10].

To harness the creative potential of artist-engineer collaboration, it is important to have a common ground. In engineering, this is done with design documents including a requirements
list. In art, this is done on a more raw level with drawings, images, phrases, and sketch models. Axiomatic Design presents an abstract way to join these two worlds by making a more abstract analysis of needs. In the case of the artists, the use of phrases in “feeling Requirements” (FRs) can easily be guided toward “Experiences” and “Feelings”. The engineers can then take these seemingly-vague requirements and try various implementations (DPs) to meet them, using the artist himself as the heuristic. Without the ability to test a requirement, it cannot be met [25]. Once this hurdle has been overcome, these design documents become the common language to make sure that what the engineers make is able to create the experience desired by the artist. As an added benefit, AD analysis can be used to improve the longevity of a work and ability to be finished on time by identifying problem elements in coupling. We believe that with such tools to make communication easier, engineer-artist collaborations can greater flourish especially in fields such as product design.

References