Development of the Human Scale
Twelve-Node Model

California Polytechnic State University, San Luis Obispo
Architectural Engineering

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I. Definitions

ARCE = the Architectural Engineering major
ARCE-211 = Structures I course, statics as applied to axial force members, taught to ARCE, CM, & ARCH students
ARCE-212 = Structures II course, statics as applied to bending members, taught to ARCE, CM, & ARCH students
ARCH = the Architecture major
CAED = the College of Architecture and Environmental Design
Cal Poly = California Polytechnic State University, San Luis Obispo
CM = the Construction Management major
PVC = polyvinyl chloride, a synthetic plastic polymer
Slip Time = additional time set aside in schedule beforehand for unknowns, setbacks
TACTivity = tactile activities designed to promote active learning
1.0 Introduction

The senior project discussed in this report involved the creation of a human scale twelve-node model with the ability for members to attach and detach efficiently. The model was to consist of PVC pipe and golf ball pinned joints, as shown in Figures 1 and 2 below.

The joints were made to be a part of a single-story, two bay by three bay structure. A plan view showing what constitutes a bay is shown for reference in Figure 3, below.

Upon completion of the physical structure, the model was to be placed on Dexter Lawn on the California Polytechnic State University, San Luis Obispo campus and used in ARCE-211 and ARCE-212 classes during week 9 of winter quarter in 2022. In these two second year ARCE courses, the twelve-node model is a major project, serving as a hands-on opportunity for students to experience and analyze stability and restraint of points in three dimensions. The structure was to be made as a way of emphasizing CAED’s focus of “learning by doing” rather than sticking to “lecture and learn.” In the past, these courses have required students to make their own small, to-scale twelve-node models out of wooden dowels and cardboard. The human scale structure
allows students to have access to both a group dynamic and physical interaction with beams, columns, braces, and joints at full size.

The project is deemed to be The Development of the Human Scale Twelve-Node Model. The term “development” indicates the process of creating or advancing something and is often used in the world of structural engineering and construction. Development in this project was not simply building a structure. The project consisted of three major focuses which were:

• following professional practice to replicate industry-like conditions,
• designing a constructable joint configuration for the model, and
• physically building the full-scale structure for use in ARCE classes.

In reproducing a professional environment, the student was tasked with learning and experiencing how to:

• meet deadlines,
• confirm and achieve desired goals and deliverables,
• prepare for and attend two meetings per week,
• be clear in communication,
• work backwards to set a schedule, and
• take safety and storage measures.

The design aspect of the project was key to construction of the twelve-node model. Golf balls and various PVC pipe fittings were used to incorporate beams, columns, and braces efficiently at each joint. Design involved:

• determining and organizing efficient joint fittings,
• creating eccentricity through golf balls,
• analyzing stability through calculations, and
• ensuring constructability of the joints.

Regarding construction, the keys were:

• being able to attach and detach members easily,
• adjusting to issues while physically building the structure, and
• gaining experience learning from failure.

The senior project was completed by Tebrez W. Khan during the winter quarter of 2022. However, the project could not have been done without the help of Professor Craig Baltimore,
CAED support shop Lab Technician Vincent Pauschek, several CAED student shop assistants, and students in the ARCE-211 and ARCE-212 classes.
2.0 Background

The full-scale structure was created to help students learn about stability and restraint of points in a tactile way. Research was done on the importance of tactile learning in addition to the usual lectures in school.

2.1 The 12-Node Model

The joints in the twelve-node structure are modeled as pin joint points. Therefore, each golf ball pinned joint needs to be restrained in three directions: “x”, “y”, and “z.” The goal is to achieve stability by stopping the movement of points in these directions, providing a path for PVC pipe members to take load to the ground. The PVC pipe members are axial members with applied forces acting along their longitudinal axis. The joints are pinned connections, which transfer loads in the vertical, “y”, and horizontal, “x” direction and allow rotational forces. As columns are used at each of the twelve nodes, the “y” direction is secured. Therefore, the focus of the exercise is restraining the “x” and “z” directions. Figure 4, below, shows reactions and forces for different connection types.

2.2 Learn-by-doing

Being able to stabilize a three-dimensional structure is a major component of the ARCE program at Cal Poly. The ARCE major is a part of CAED, which, as the university does, focuses on combining lecture with hands-on learning. The school motto is “learn by doing” which comes from the idea that students achieve higher learning from experiencing examples of what is taught in lecture. Tactile, or experiential learning is one method in the learning pyramid. By using experiential learning, as opposed to the simple reading, auditory, and visual forms of education, humans can excel in sustaining knowledge rather than memorizing information. Tactile activities, or TACTivities, allow humans to increase their attention spans, as well as promote
engagement and excitement towards the subject. While lectures enforce memorization in an “algorithmic way,” doing experiential activities enforce problem-solving skills instead (Hodge-Zickerman et al.).

ARCE-211 and ARCE-212 are known as the “Structures I” and “Structures II” courses, respectively. ARCE-211 is defined as an “introduction to statics and creation of simple three-dimensional structures” and the analyzation of “structures composed of axial force (truss) members.” ARCE-212 is defined as an “introduction to shear and moment diagrams using the principles of statics and the application of the diagrams to simple three-dimensional structures” (“Architectural Engineering”). For those in these classes, working with a human scale, physical twelve node model accomplishes CAED’s goal of gaining valuable tactile experience. Research indicates that approximately 70% of one’s learning comes through experience. Just 20% comes from others, such as coaches, mentors, and peers. The additional 10% is the standard, structured courses taken in school (“The 70-20-10 Rule”). The various forms of learning are represented below in Figure 5.

Since construction involves physically building structures, structural engineering is a profession that requires professionals to fully understand concepts, such as stability. Therefore, incorporating tactile learning projects in addition to the traditional lectures is quite beneficial for aspiring engineers.

![Figure 5. The 70-20-10 Rule of Learning](https://leadershippipelineinstitute.com/products-the-702010-model)
3.0 Professionalism

Replicating an industry-like professional environment over the duration of the project was a significant focus of both the student and advisor. Professionalism was incorporated into the project by emphasizing the importance of and adhering to meetings and schedules.

3.1 Meetings

The student and advisor created a schedule of two meetings per week. One meeting, known as the early-week meeting, was every Tuesday at 10:00 A.M. in the advisor’s office. The second meeting, known as the late-week meeting, took place Thursday at 10:00 A.M. in the advisor’s office. During these meetings, the student and advisor discussed the goals for the immediate future and the respective deliverables required to achieve these goals. Regardless of meeting length, it was important that contact was made between the student and advisor in order for the project to progress and for meetings to become a part of both parties’ routines.

In addition to attending one early-week and one late-week meeting, the student was tasked with confirming and summarizing the desired goals and deliverables discussed in a follow-up email to the advisor within 24 hours of meeting time. This allowed there to be clear communication and had the student and advisor coordinated with each other regarding deadlines.

Additional meetings were held with Vincent Pauschek, a CAED Support Shop Technician, and Dr. Allen Estes, the ARCE Department Head to discuss the project. The student learned about proper preparation for such meetings, and the immense value of revisions while writing a report, email, memo, or any other form of writing in the professional field.

A great example of the lesson learned regarding the power of revisions was the Material Cost Sheet created to get approval for funding. As is provided in Appendix A, the original copy of the Material Cost Sheet was quite simple and unprofessional. After review with the advisor and adjusting to create a proper report, the final result was unrecognizable from the first draft. The revised sheet is provided in Appendix B.

3.2 Schedule & Planning

The big key to scheduling for the project was working backwards. The Development of the Human Scale Twelve-Node Model was a unique senior project, as the final structure needed to be in use at the beginning of week 9 of winter quarter. This meant that the construction needed to be complete week 8. To accomplish this feat, the final joint design and initial build to check viability of the design had to be done first. Like on a construction site, some tasks were
dependent on others being completed. Figuring out the schedule of all the tasks having to do with the project had to be thought of ahead of time by working backwards. Working backwards allowed the student and advisor to have a plan for earlier deadlines so the later tasks and overall schedule would not be affected. Allotting additional time for unknowns, a concept known as “slip time,” was used during this project. An additional week was set aside for potential setbacks, and this slip time was used up during the project for a variety of reasons. An ARCE administrator was sick for a few days, delaying the purchase of materials for the initial build. The retail store responsible for the project’s supply of PVC pipe members sent out the wrong sized pipe, which was not checked until the student cut the members for the initial build. A change to the joint design configuration was made during the initial build. The CAED Shop Technician had to move shelves and the lab room, known as the High-Bay Lab, was unavailable, so the drill used for all golf balls and end caps was non-operational for a day when it was needed. These examples showed the importance of not scheduling every little task to a tee and allowing time for the unknowns. The overall schedule of the tasks for the project are displayed in Figure 6 below.

![Construction Gantt Chart](image)

*Figure 6. Overall Schedule Gantt Chart*

Additional planning had to be done in order to ensure structure safety and storage. Since the full-size model was to be displayed on Dexter Lawn on the university campus for students to use during class, vandalism had to be considered. Not only was the structure to be on campus while ARCE classes used the model, but the model would be left overnight. To combat people from damaging the project, yellow tape and signs would be displayed. Sandbags were to be used not only to weigh down the structure for use while students adjusted brace members, but also to prevent people from trying to take the project apart.
4.0 Design Configuration

The initial design configuration was a simple concept on paper, with concentric three-dimensional pin joints. The purpose of the human scale model was to have students in ARCE-211 and ARCE-212 stabilize these points in the model. Since the students were going to determine the necessary number of beams, columns, and braces to provide sufficient stability in the structure, the design needed a balance of being put together well and having the ability for pipes to be efficiently attached and detached. Joints were configured using a variety of PVC fittings, as well as a golf ball and end cap bolted connection.

4.1 PVC Fittings

Beams and columns used in the created model were approximately 5 foot long, 1 inch PVC Schedule 40 pipes. The pipes were connected at each of the twelve nodes using 3 types of PVC fittings. To connect these horizontal and vertical members of the structure, “tees” were used as fittings. There were 3 types of tees used, each with a different number of openings to accommodate a different number of members coming into the tees, as will be discussed further in section 5.1. Figures 7, 8, and 9.

![Figure 7. 3-Way Tee](image)

![Figure 8. 4-Way Tee](image)

![Figure 9. 5-Way Tee](image)
These tees allowed pipes to be at 90-degree angles to create the basic 2 bay by 3 bay model without any diagonal members. An example of the result of only 90-degree members is shown in Figure 10 below.

![Figure 10. Isometric View of 90 Degree Members Only](image)

The multiple colors used to illustrate columns indicate the three types of joints they are attached to, as will also be noted later in section 5.1.

The way to stabilize the nodes in the twelve-node model was to add the necessary number of 45-degree braces to the structure. To support the beams and columns with braces, additional connections needed to be added at each node.

“Wyes” were the PVC connection of choice to get the desired 45-degree angle between members. Two different wyes were used. There were 46 braces and just 29 columns and beams in the completed model. Since there were more diagonal members, the 3-way wye, as show below in Figure 11, was the most prevalent of any of the PVC fittings used. The addition of the 3-way wye to a pipe member will be shown in Figure 14 in section 4.2. The 4-way wye shown in Figure 12 was used only to connect members at the ground level of the model.

![Figure 11. 3-way Wye](image) ![Figure 12. 4-way Wye](image)
Like the beams and columns in the model, braces were all 1-inch PVC Schedule 40 pipes. The braces were just at longer lengths than the 90-degree members. However, since there are no 4-way wyes fittings made to fit 1-inch members, 1.5-inch fittings were purchased. In order to deal with the variance in pipe and fitting size at these connections an extra piece was needed to mitigate the size difference. A 1 inch to 1.5-inch bushing reducer, which allowed the connection of the member to the wye using its different diameter openings on each side, was used. The reducer bushing is displayed in Figure 13, below.

![Figure 13. 1” to 1.5” Bushing Reducer](image)

### 4.2 Golf Balls & End Caps
Golf balls were used to get pin connections at the end of each member in the configuration. To accomplish this during construction, holes were drilled through the center of the golf balls as well as the center of PVC end caps, which were shown in Figure 1 in section 1.0. The end caps and golf balls were bolted together and tightened, which resulted in them acting as one piece. The pieces were attached between each PVC fitting, regardless of whether it was connecting a wye to a tee, or a wye to a wye. This process was achieved using a heat gun, which heat up the PVC fitting enough to stick the golf ball in, leaving one quarter of an inch of the ball exposed. The golf balls were connected to the fitting, while the open end of the caps faced outwards to connect to the pipe members. The connection of the golf ball and end cap to the pipe member is shown in Figure 14, below.

![Figure 14. Golf Ball to Pipe Member Connection](image)
5.0 Schematics

Schematic drawings were instrumental to the development of the design configuration over the course of the project. The student worked on Microsoft Whiteboard to visually convey the member and joint connections necessary for both the initial and final build. Sketches, plan view, and isometric view drawings, as shown in section 4.1, were utilized as communication between the student and advisor. The final model was constructed by the CAED Support Shop Lab Technician, Vincent Pauschek, and several student support shop assistants. Thus, communication sketches were provided to the support shop for proper construction.

5.1 The 3 Types of Nodes

The final structure in the project involved a total of 94 PVC connections, 24 of which were necessary at the ground level of the model. The 70 connections located as part of the 12 golf-ball pinned joints comprised of both tees and wyes.

Three different types of nodes were present in the twelve-node model, those being:

- corner joints,
- side joints, and
- middle joints.

As mentioned in section 4.1, three different tees were utilized in the structure to accommodate the 3 types of joints. Figure 15 below shows the number of members connecting to each of the twelve joints. There were 6 members meeting at the joints in the corners of the model. There were 9 members meeting at the joints on the sides of the model. There were 13 members meeting at the 2 middle joints of the model.

![Figure 15. Number of Members Meeting at Nodes](image-url)
Like was shown in the isometric view of Figure 10 in section 4.1, the dark blue color indicates corner joints, while green joints indicate side joints, and red joints indicate middle joints. The purple diagonal lines represent braces occurring from joint to joint, while light blue and yellow lines represent braces going from joints to the ground level.

5.2 Member Connections

Corner joints involved 3 beams and columns, or members oriented at 90 degrees. Accordingly, 3-way tees were used at these locations. Additional connections were 3-way wyes, used to meet 45-degree braces. An example of a corner joint is shown in Figure 16.

Side joints needed connections for 4 beams and columns, and therefore used 4-way tees. Figure 17 provides an example of a side joint with the 1 tee and 5 3-way wyes used.

There were 5 beams and columns and 8 braces meeting at middle joints. A 5-way tee and 8 3-way wyes were used for each of these joints, as represented in Figure 18.

The orange fittings represent 3-way wyes, while the other colors in Figures 16, 17, and 18 represent the tees used.

A bushing reducer, as discussed in section 4.1, was used for the 4-way wyes. These fittings were used only at the ground level, where columns and braces met below each of side and middle nodes.
6.0 Construction

What appeared on the surface to be a simple structure turned out to be a challenging structure to construct. An integral part of the 12-Node Model pertinent to this senior project was the concept of having pinned joints. The viability of these joints proved to vary significantly when comparing structural theory with physical construction. While on paper the three-dimensional pin joints were concentric, the real joints could not be constructed without some eccentricity in the point.

6.1 Theory vs. Practice

Theoretically, the use of a pinned joint at the end of a beam is common procedure. Based on knowledge acquired during previous ARCE lectures, the procedure requires the 3-dimensional members to be modeled as 2-force members with pinned ends. The joints need to be able to rotate. It turned out that in practice, it is difficult to physically construct true 3-dimensional pinned connections. While this is not the case if the structure required concentric pinned joints, the 12-Node Model in the senior project required eccentric pinned joints.

The variance between concentric and eccentric joints is not an issue in structural theory. This is due to the practice of working with “small displacements.” ARCE students have learned that small displacements tend to correlate with having between a 0.0001 and 0.01 normal strain. Figures 19 and 20, below, depict the difference in small versus large displacements at the connections.
As shown in Figure 19, small rotations are negligible which allows the structure to maintain stability. However, Figure 20 shows that the eccentric joint pops up due to the large displacement in the form of a rotation.

6.2 Learning by Failing

The results shown in Figure 20 caused an unstable structure. As far as the initial structure built for the senior project was concerned, the need to accommodate the diagonal brace caused each joint to get bigger. This caused joints to have dimensions which are typically negligible in theoretical practice.

Each golf ball in the physical structure represented an eccentric point. A simply supported beam, the basis of theoretical beam design, has two ends. Each end has a support that allows rotation. However, when the initial structure for the senior project was built, the beam had three points acting as hinges between supports, and the beam was unstable. This concept is shown in Figure 21, below.

![Figure 21. Simple Structure Stability Comparison](image)

The result of this issue was the need for the student and advisor to alter the design configuration of the model. Multiple attempts to adjust the design were made. The new ideas included:

- eliminating end caps used to connect multiple wyes from the structure,
- using couplers to connect the tees with the wyes, and
- eliminating vertical braces and focusing solely on horizontal braces.

The couplers referred to, above, were 1.25-inch-long PVC pipe members fit in between tees and wyes and secured with PVC paste to fasten the connections. These changes allowed for smaller dimensions in the joints and more stability due to less golf ball pinned points.

While the alterations to plan such as the design configuration and schedule throughout the project were disappointing and frustrating, they were essential learning experiences for the student. The student gained an understanding for the need to leave significant slip time for such circumstances, as well as keeping an eye out for possible issues throughout every step of a project. The student and professor kept level heads, allowing for the ability to make the necessary adjustments and focus on the next step rather than dwelling on the past.
Pictures documenting the large rotations and deflections posed by the 3 variations of the initial build are provided in Appendix C.

6.3 Precedent

The student studied and incorporated gained knowledge from a previous senior project conducted under the advisement of Professor Baltimore. A senior project, “The Project Management of Investigating Dowel Laminated Timber,” conducted by former students Reiley Akkari, Bryan Garcia, and Sophia Looney, involved learning by failing. The group project took place in winter quarter of 2020 and consisted of three students investigating dowel laminated timber “through fabricating specimens” in a hope to “improve professional standards” of the profession (Akkari et al.). The investigation and analysis in the project were done using similar tools to those used in third-world countries. The students investigated the “worst case” scenario in construction of dowel laminated timber members. This allowed for simulating improper design and construction that was possible in developing nations. Figure 22 shows that all 2x4’s had a single dowel for continuity. However, the slab was a bending member that has a force couple, and therefore, two dowels spaced apart were required at minimum. Where there was to be a 2-inch spacing between dowels, turned out to have a far worse case of 16 inch spacing.

Accordingly, the moment arm was 8 times larger for the worst case than for the 2-inch spacing scenario, and thus the moment was 8 times larger, as well.

While the senior project described above is quite different from the Development of the Human Scale Twelve-Node Model, the idea of gaining experience of failing and learning from mistakes was applicable to both projects. By actually building the multiple initial renditions of the 12-node structure, the student was able to relate the concept of hinges and stability taught in lecture to a physical structure. This allowed the concept of constructability to be front and center in the project. Professor Baltimore and other ARCE faculty have emphasized constructability, so students keep the concept in mind while designing members and connections in industry.
7.0 Revised Model

As a result of the issues mentioned in sections 6.1 and 6.2, the design configuration was refined to reduce the eccentricity in the golf ball pin joints. Vertical braces connecting to each joint were removed from the model. Due to the added time, it took for designing and constructing 3 variations of the initial build, as well as having less CAED support shop assistants available for final construction as was initially expected, 2 bays were eliminated from construction. The final build was a 2 bay by 2 bay structure at full scale.

7.1 Joints

With the delays that occurred throughout the project, there was a time crunch at the end of the winter quarter for construction. Less CAED support shop assistants were available as promised at the beginning of the quarter. The student created an instruction sheet to assist in the ease of manufacturing the golf ball joint configuration. However, when extra golf balls were added into PVC tees that were specifically labeled to not have golf balls attached, the time push-back increased. During finals week, the student worked on the construction alone, as the CAED support shop assistants were unavailable. The final joints and created bays during the construction process are depicted below in Figures 23 and 24 respectively.

![Figure 23. Constructed Joints with Golf Balls](image1)

![Figure 24. Bays Created During Construction](image2)

Despite the construction of bays taking place, a final issue was found in the design of the human scale model. The base of the model was made of the same tee connections used at the 12 nodes. In order to maintain a fully pinned 3-dimensional model, the columns were all pinned at the base.
The issue that arose, as shown in Figures 25 and 26, was rotations occurring due to the length of the columns and mass of the structure that the base supported. Because of this, adding sandbags, or in this case lumber for weight, held the structure down but could not prevent this rotation from occurring to any east-west load such as a point load or wind.

![Figure 25. Angled Column due to Rotation at Pinned Base]

![Figure 26. Angle Occurring at Base]
8.0 Conclusion

This project was definitely one of the greatest experiences I had in college. As someone who did not know what they wanted to do going into college, I have fallen in love with structural engineering over my years at Cal Poly. The ARCE program has had a great mix of learning by doing and learning by failing. Gaining experience in structural calculations, member design, hands-on construction, and construction management have led to this project.

While the results of the final construction were not what we had hoped for at the beginning of the quarter, I do not think I could have learned more and gained more valuable insight into the industry than I did. There were countless issues that arose over the course of the senior project, from incorrect material deliveries to adjusting joint configurations multiple times. Overall, these issues led to a time crunch for a solo project in less than 10 weeks.

In order to perfect the design of a human scale twelve-node model in a future senior project, there are some valuable insights I learned that I believe would make for a smoother project. I would suggest the project to be conducted by 2 to 3 students rather than 1. Not only would joint manufacturing time decrease with more people available, but actually putting together the full 6 foot high, 18 foot by 12-foot model would be a lot easier to work with if multiple people were doing the project. The actual joint configuration has been determined and the only part of the structure that remains an issue is the base. The rotation occurring at the base of the structure due to the large column length and structure’s mass has to be resisted through either screwing the bottom of the PVC connection into the ground but maintaining pins at the base or a new idea. The idea of the set screw into the bottom of the connection is not ideal as the structure was to be removed and placed on the Dexter Lawn grass easily and screwing into the ground would be a more permanent solution than the temporary one needed.
9.0 References


## 10.0 Appendix

### 10.1 A

The original material cost sheet prior to revisions

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<td>$15.60</td>
</tr>
<tr>
<td>100</td>
<td>$43.99</td>
<td>100</td>
<td>1</td>
<td>$43.99</td>
</tr>
<tr>
<td>100</td>
<td>$14.05</td>
<td>100</td>
<td>1</td>
<td>$14.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$324.49</strong></td>
</tr>
</tbody>
</table>
10.2 B

The updated material cost sheet after revisions

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**Senior Project**

**Full Scale 12-Node Model**

by: Tefrez Khan

Advisor: Prof. Baltimore

**Initial Materials Budget**

**Project Description**

The senior project goal is to create the 12-node stability model used in both ARCE-211 & and ARCE-212 classes at human scale, out of PVC pipe. The project will involve professional project management processes, structural calculations, connection design configuration, and actual construction.

Figure 1, below, shows the required configuration for the 12-node model. The various colors highlight the different PVC connection types, while yellow and light blue lines indicate brace members going to the ground level.

![Figure 1. Member & Joint Configuration](image)

Connections of the pipe members are key to constructability of the human scale model. Figure 2, below, shows an example of a connection, with the blue circles being golf balls screwed in for eccentricity purposes.

![Figure 2. Example Connection Detail](image)
Senior Project Full Scale 12-Node Model by: Tebrez Khan
Advisor: Prof. Baltimore

Initial Budget

Tables 1 & 2 are the material costs for the full project and the initial one-bay build, respectively. It is the intent to apply for Senior Project Scholarships and/or Learn-by-Doing ARCE Department funding. However, such funding will not be available until Spring Quarter. Construction in time for ARCE-211 & ARCE-212 classes to use the full-scale model requires materials immediately.

Table 1. Full Project Material Cost

<table>
<thead>
<tr>
<th>Store</th>
<th>Item</th>
<th>Total Count Req</th>
<th>Package Cost</th>
<th>Count in 1 package</th>
<th>No. Packages Req</th>
<th>Item Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>3-way Tee (90 deg)</td>
<td>4</td>
<td>$18.59</td>
<td>8</td>
<td>1</td>
<td>$18.59</td>
</tr>
<tr>
<td>Amazon</td>
<td>4-way Tee (90 deg)</td>
<td>6</td>
<td>$12.45</td>
<td>2</td>
<td>3</td>
<td>$37.35</td>
</tr>
<tr>
<td>Amazon</td>
<td>5-way Tee (90 deg)</td>
<td>2</td>
<td>$18.59</td>
<td>8</td>
<td>1</td>
<td>$18.59</td>
</tr>
<tr>
<td>PVC Pipe Supplies</td>
<td>3-way Wye (45 deg)</td>
<td>75</td>
<td>$2.09</td>
<td>1</td>
<td>75</td>
<td>$156.75</td>
</tr>
<tr>
<td>PVC Pipe Supplies</td>
<td>4-way Wye (45 deg)</td>
<td>10</td>
<td>$8.59</td>
<td>1</td>
<td>10</td>
<td>$85.90</td>
</tr>
<tr>
<td>Home Depot</td>
<td>PVC Pipe (20 ft)</td>
<td>30</td>
<td>$16.96</td>
<td>1</td>
<td>30</td>
<td>$508.80</td>
</tr>
<tr>
<td>Amazon</td>
<td>End Caps</td>
<td>100</td>
<td>$28.04</td>
<td>25</td>
<td>12</td>
<td>$336.48</td>
</tr>
<tr>
<td>Amazon</td>
<td>Golf Balls</td>
<td>100</td>
<td>$43.99</td>
<td>100</td>
<td>3</td>
<td>$131.97</td>
</tr>
<tr>
<td>Home Depot</td>
<td>Reducers</td>
<td>30</td>
<td>$2.16</td>
<td>1</td>
<td>30</td>
<td>$64.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total =</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,350.23</td>
</tr>
</tbody>
</table>

Before all materials are purchased in their entirety, the goal is to create (1) out of the (6) bays to prove constructability & quality of both materials and design configurations. Table 2, below, shows the costs of this initial build.

Table 2. Initial Build Material Cost

<table>
<thead>
<tr>
<th>Store</th>
<th>Item</th>
<th>Initial Count Req</th>
<th>Package Cost</th>
<th>Count in 1 package</th>
<th>No. Packages Req</th>
<th>Item Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>3-way Tee (90 deg)</td>
<td>0</td>
<td>$2.09</td>
<td>0</td>
<td>0</td>
<td>$2.09</td>
</tr>
<tr>
<td>Amazon</td>
<td>4-way Tee (90 deg)</td>
<td>2</td>
<td>$12.45</td>
<td>2</td>
<td>3</td>
<td>$37.35</td>
</tr>
<tr>
<td>Amazon</td>
<td>5-way Tee (90 deg)</td>
<td>2</td>
<td>$18.59</td>
<td>8</td>
<td>1</td>
<td>$18.59</td>
</tr>
<tr>
<td>PVC Pipe Supplies</td>
<td>3-way Wye (45 deg)</td>
<td>30</td>
<td>$2.09</td>
<td>1</td>
<td>30</td>
<td>$62.70</td>
</tr>
<tr>
<td>PVC Pipe Supplies</td>
<td>4-way Wye (45 deg)</td>
<td>6</td>
<td>$8.59</td>
<td>1</td>
<td>6</td>
<td>$51.54</td>
</tr>
<tr>
<td>Home Depot</td>
<td>PVC Pipe (20 ft)</td>
<td>6</td>
<td>$16.96</td>
<td>1</td>
<td>6</td>
<td>$101.76</td>
</tr>
<tr>
<td>Amazon</td>
<td>End Caps</td>
<td>75</td>
<td>$28.04</td>
<td>25</td>
<td>3</td>
<td>$84.12</td>
</tr>
<tr>
<td>Amazon</td>
<td>Golf Balls</td>
<td>100</td>
<td>$43.99</td>
<td>100</td>
<td>3</td>
<td>$131.97</td>
</tr>
<tr>
<td>Home Depot</td>
<td>Reducers</td>
<td>25</td>
<td>$2.16</td>
<td>1</td>
<td>25</td>
<td>$54.00</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Total =</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$429.15</td>
</tr>
</tbody>
</table>
The top five items in both Table 1 & 2 are less familiar, and therefore pictures of those items are below.

Figure 3. 3-way Tee
Figure 4. 4-way Tee
Figure 5. 5-way Tee

Figure 6. 3-way Wye
Figure 7. 4-way Wye
PVC Reducer
10.3 C
These are pictures of the 1st variation of the initial build. Large deflections and rotations are apparent, as well as large eccentricities of the golf ball pin joints.
These are pictures of a revised variation of the initial build. This design configuration lowered the amount of eccentricity present and reduced the number of golf balls and wyes used in the structure.