<table>
<thead>
<tr>
<th>Name</th>
<th>University</th>
<th>Position</th>
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</thead>
<tbody>
<tr>
<td>Simge</td>
<td>Stanford University</td>
<td>Construction Manager</td>
</tr>
<tr>
<td>Tianlong</td>
<td>Stanford University</td>
<td>Structural Engineer</td>
</tr>
<tr>
<td>Ronja</td>
<td>Aalborg University</td>
<td>Architect</td>
</tr>
<tr>
<td>Jacob</td>
<td>Technical University of Denmark</td>
<td>Construction Manager</td>
</tr>
<tr>
<td>Sebastian</td>
<td>Bauhaus University</td>
<td>Structural Engineer</td>
</tr>
<tr>
<td>Nicolas</td>
<td>Zurich University</td>
<td>MEP Engineer</td>
</tr>
</tbody>
</table>
Project area

Av. Universidad, San Juan, Puerto Rico

Construction site
Mood board

Colorful and vibrant

Activities

Nature

Disasters

Post-Disaster
Climate of Puerto Rico

Wind rose

- Stable Wind Direction
- High Temperatures
- High Relative Humidity
- Yearly High Sun
- Rain reduction

Monthly rainfall

- Precipitation Events

Temperature and sun hours

Earthquake

- Risk Category: III
- Site Category: D

Wind (Hurricane)

- Design Wind Speed: 175 mph
- Hurricane Maria: Category 5
Goals

Modern Educational Building

Building for Puerto Ricans

Resilient
Rainbow
and sun

AFTER RAIN THERE’S A RAINBOW
AFTER A STORM THERE’S CALM
AFTER THE NIGHT THERE’S A MORNING
AND AFTER AN END
THERE’S A NEW BEGINNING
Concept
Psychology of colors

<table>
<thead>
<tr>
<th>Clarity</th>
<th>Friendliness</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warmth Optimism</td>
<td>Cheerful Enthusiasm</td>
<td>Passion Appetite</td>
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<table>
<thead>
<tr>
<th>Health</th>
<th>Wisdom</th>
<th>Peace</th>
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<tbody>
<tr>
<td>Nature</td>
<td>Royalty Creativity</td>
<td>Security Reliability</td>
</tr>
<tr>
<td>Wealth</td>
<td></td>
<td></td>
</tr>
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</table>
Development of design

- Placing footprint
- Color coding boxes
- Placing boxes in grid
- Structural grid
View from Northern entrance
Flow

Main Circulation

Means of egress
Communal staircase
View from intersection
LED screen
Structural material

Material options

Steel
- Lighter weight
- Earthquake performance

Concrete
- Local expertise
- Cost reduction
- Recycle concrete potential

Bamboo
- Local material
- Carbon footprint reduction
Site conditions

Soil profile
- Bearing capacity = 5000 psf
- Maximum soil pressure = 1-story height

Response spectrum
- $S_{DS} = 0.72g$
- $S_{D1} = 0.42g$
- Importance factor = 1.25
## Dead load

### Concrete option

### Steel option

### Bamboo roof

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight (psf)</th>
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</thead>
<tbody>
<tr>
<td>PT Slab 9”/Composite Metal Deck 7 1/4”</td>
<td>112/56</td>
</tr>
<tr>
<td>Insulation</td>
<td>3</td>
</tr>
<tr>
<td>MEP</td>
<td>6</td>
</tr>
<tr>
<td>Floor finishes</td>
<td>30</td>
</tr>
<tr>
<td>Partitions</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>166/110</strong></td>
</tr>
<tr>
<td>Bamboo structure</td>
<td>45</td>
</tr>
<tr>
<td>Decking 3-in</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>53</strong></td>
</tr>
</tbody>
</table>
Live load

125 psf
100 psf
40 psf

<table>
<thead>
<tr>
<th>Location</th>
<th>Load (psf)</th>
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<tbody>
<tr>
<td>Offices</td>
<td>50</td>
</tr>
<tr>
<td>Lounge</td>
<td>100</td>
</tr>
<tr>
<td>Auditorium</td>
<td>100</td>
</tr>
<tr>
<td>Server Room and Lab</td>
<td>100</td>
</tr>
<tr>
<td>Storage Room</td>
<td>125</td>
</tr>
<tr>
<td>Classrooms</td>
<td>40</td>
</tr>
<tr>
<td>First-floor Corridor</td>
<td>100</td>
</tr>
<tr>
<td>Corridor above first floor</td>
<td>80</td>
</tr>
<tr>
<td>Roof</td>
<td>20</td>
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</tbody>
</table>

Ground level
Lateral load

<table>
<thead>
<tr>
<th>Force (kip)</th>
<th>Wind</th>
<th>Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Windward</td>
<td>Leeward</td>
</tr>
<tr>
<td>F3</td>
<td>75.6</td>
<td>21.1</td>
</tr>
<tr>
<td>F2</td>
<td>101</td>
<td>26.4</td>
</tr>
<tr>
<td>F1</td>
<td>64</td>
<td>15.8</td>
</tr>
<tr>
<td>Base Shear</td>
<td>303</td>
<td></td>
</tr>
</tbody>
</table>

Ta = 0.37 sec → Earthquake
Evolution of ideas

**Kick-off**
- January
  - **X** Base isolated foundation
  - **X** Seismic joint
  - **X** Cantilever - truss
  - **?** Auditorium truss
  - **X** CM-CR = 20’
  - **X** Short column!
  - **✓** PT tapered beam
  - **?** Auditorium truss

**1st Mentor Session**
- March

**Peer Review**
- February
  - **✓** CM-CR = 2.5’
  - **✓** Concrete rigid panel
  - **✓** Auditorium truss

**2nd Mentor Session**
- March
Structural system solutions

Steel solution

Concrete solution

Bamboo roof

BRB

Shear wall

Slanted column

Shear wall

Tapered PT beam
Basement

Auditorium

Isolated Foundations 7.5’x7.2’x20”
Grade Beam 16”x16”
Wall Foundation 36”x24”
Retaining wall 10”
First floor

<table>
<thead>
<tr>
<th>Concrete Solution</th>
<th>Steel Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>8” Concrete Rocking Wall</td>
<td>8” Concrete Rocking Wall</td>
</tr>
<tr>
<td>10”x15” Concrete Beam</td>
<td>W12X87 Beam</td>
</tr>
<tr>
<td>24”x10” Tapered PT Beam</td>
<td>W10X45 Slanted Column</td>
</tr>
<tr>
<td>16” Circular Column</td>
<td>W10X45 Column</td>
</tr>
<tr>
<td>Concrete Rigid Panel</td>
<td>Concrete Rigid Panel</td>
</tr>
<tr>
<td>24”x10” Tapered PT Beam</td>
<td>Tapered W27x114</td>
</tr>
</tbody>
</table>
Truss design process

A + E + MEP integration

Pros
- Deflection control
- Tensile diagonals
- Free openings
- Plastic behavior

Cons
- No openings
- No plasticity
- Deeper sections

Middle openings (Arch)
- Deflection control
- Plastic behavior
- Depth reduction (MEP)
Truss design process

A + E + MEP integration

Gravity load - MASTAN2, 2nd order analysis:

Long Span = 58’
Deflection ~ 0.5”
Deflection < L/360
Vertical: W8x31
Diagonal: W8x31
Horizontal: W12x87

Pushover analysis from ETABS:
Gravity load path
Lateral load path

Steel solution

Concrete solution

Steel BRB

Shear wall
Embrace natural ventilation and the climate

Climate zones as division of private/public

Color coding of MEP system for user education
Design strategies

- Sun Shading
- Natural Ventilation
- Night-Cooling
- Fans
- Active Systems where needed
Comfort conditions

Operative Temperature

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature</th>
<th>Air Speed</th>
<th>Relative Humidity</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>26 °C</td>
<td>0.1 m/s</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>28 °C</td>
<td>0.8 m/s</td>
<td>75%</td>
</tr>
</tbody>
</table>

Source: CBE Thermal Comfort Tool
Both scenarios for metabolic rate of 1 met and clothing level of 0.5 clo
High-tech system option

Primary Systems
- Source
- Conversion
- Decentralized AHU for dehumidification
- Outside Air
- Heat Exchanger
- Plenum Distribution / Ducts

Secondary Systems
- Storage
- Distribution
- Emission
- Cool Water Pipes
- Ceiling Grilles
- Passive Chilled Beams
- Chilled Water Plant

Decentralized AHU
Chilled Water Plant
Plenum Air Distribution
Passive Chilled Beams
Fan-assisted system option

Primary Systems
- Source
- Conversion
- Ground Water
- Water / Water Heat Pump
- Outside Air
- AHU on roof

Secondary Systems
- Storage
- Distribution
- Emission
- Ceiling Fans
- Ducts
- Vent Grilles

Water/Water Heat Pump
- Central Roof AHU
- Reduced cooling/dehumidification

Fan-Assisted local comfort

Electricity
Hot Transfer
Cool Transfer
Distribution tree

High-tech system

Basement

Ground floor

First floor

Supply Air
Return Air
AHU’s
Distribution tree

Fan-assisted system

Basement

Ground floor

First floor

Supply Air
Return Air
Fans
Section

Ventilation and water collection
Floor sandwich

High-tech system
Floor sandwich

Fan-assisted system
More details

Water collection and HVAC color coding

Red = Return  
Blue = Supply

Water Collection and HVAC Color Coding

Max. Monthly Water Collection from Roof Surface

Roof Srf = 17'000 sf

Average Rainfall [in]

Proposed Water Tank Capacity

Current Weather  Predicted Climate Change 2050

Graph showing monthly water collection and average rainfall with color coding for return and supply.
Site access

Traffic conditions
Site access

Truck flow - entrance

Highway 27

Construction Site
Site access

Truck flow - exit

Ave. Juan Ponce de Leon

Construction Site
Site plan - Rainbow steel alternative

- Waste/recycling area
- Material laydown
- Toilets
- Site offices
- Parking area
- Equipment parking
- Emergency evacuation
- Heavy vehicle route
- Lightweight vehicle route
- Mobile crane 80 ft diameter
- Tire wash

Tire wash
Site plan - Rainbow concrete alternative

- Material laydown
- Toilets
- Site offices
- Parking area
- Equipment parking
- Waste/recycling area
- Emergency evacuation
- Tire wash
- Heavy vehicle route
- Lightweight vehicle route
- Mobile crane 80 ft. diameter
Overall Budget and Target

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Construction Grant from Donor</td>
<td>$12,000,000</td>
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<tr>
<td>Grant Year</td>
<td>2020</td>
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<tr>
<td>Construction Year</td>
<td>2024</td>
</tr>
<tr>
<td>Expected Inflation</td>
<td>2.40%</td>
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<tr>
<td>Return on Investment</td>
<td>2.20%</td>
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<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>BUDGET</td>
<td>$11,904,000</td>
</tr>
<tr>
<td>TARGET</td>
<td>$11,000,000</td>
</tr>
</tbody>
</table>

**Cost Breakdown Targets**

- **Substructure**: 9.6%
- **Shell**: 21.6%
- **Interiors**: 12.9%
- **Services**: 28.8%
- **Equipment and Furnishings**: 4.3%
- **Specialty Construction**: 8.5%
- **Building Sitework**: 6.0%
- **General Conditions**: 8.5%

Target Value Design

I. Rainbow concrete

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVENT</th>
<th>ESTIMATE</th>
<th>DELTA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target</td>
<td>$ 11,000,000</td>
<td>$ -</td>
</tr>
<tr>
<td>02/10/2020</td>
<td>RS Means Square Foot</td>
<td>$ 5.3 million</td>
<td>$ 5.7 million</td>
</tr>
<tr>
<td>02/16/2020</td>
<td>Quantity Take-off #1</td>
<td>$ 4.5 million</td>
<td>$ 6.5 million</td>
</tr>
<tr>
<td>03/07/2020</td>
<td>Quantity Take-off #2</td>
<td>$ 5.7 million</td>
<td>$ 5.3 million</td>
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</table>
II. Rainbow steel

<table>
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<th>DATE</th>
<th>EVENT</th>
<th>ESTIMATE</th>
<th>DELTA</th>
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</tr>
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<td>02/16/2020</td>
<td>Quantity Take-off #1</td>
<td>$ 8.9 million</td>
<td>$ 2.1 million</td>
</tr>
<tr>
<td>03/07/2020</td>
<td>Quantity Take-off #2</td>
<td>$ 6.2 million</td>
<td>$ 4.8 million</td>
</tr>
</tbody>
</table>

Target Value Design
Construction sequence

Rainbow

Zone 2

Zone 3

Zone 4

Zone 1

- Blue: Instructional labs
- Orange: Auditorium, small & large classrooms
- Green: Study spaces and service rooms
- Yellow: Café, toilets and service rooms
Schedule timeline

Concrete alternative

Steel alternative
Construction equipment

**LTM 1200-5.1 - Crane**

**Forklift**

**JLG-450AJ SERIES II**

- Platform Height: 45.0 ft
- Platform Length: 72.0 in
- Platform Width: 30.0 in

**CAT® LARGE EXCAVATORS 336 GC**

- Engine Power - ISO 9249
  - 273 HP
- Operating Weight
  - 80500 lb
- Maximum Digging Depth
  - 27 ft
Quality & safety on site

Utilizing technology

Drone technology for geolocation

AR technology for integrated construction and precise measurements
Material procurement

Puerto Rico, San Juan

Locations
- Steel & Pipes Inc.
- Marxuch Precast Solution
- Acha Trading – Interiors
- United Glass Co.
- Cemex
- Tesoroen Maderas – Wood
- Vista Systems – Curtain walls
- ACR Systems – HVAC
- Clary Cooperation – Electrical
- CED – PV Elements
- Construction Site
Movement
Concept
Development of design

- Placing footprint
- Focal point
- Four cores
- Placing rooms
Design iterations
Flow

Main Circulation

Means of egress
Plan

60’ × 60’

First floor

- Faculty office
- Chairs office
- Senior administration office
- Firestairs and elevator
- Toilets
- Mechanical shaft
Elevations

North

West

South

East
View from intersection
Evolution of ideas

- **Footprint**
- **Cores**
- **Dynamic shape**
- **Base-isolated Foundation**

- Torsion capacity
- High Seismic Forces
- Embracing Movement
- Resilience
Structural system solutions

**Steel solution**
- Steel bracing
- Bamboo truss
- Stunted columns

**Concrete solution**
- Base isolation
- Shear wall
**Base isolation design**

**Preliminary design (Naeim & Kelly, 1999)**

**ELF earthquake load**

- 564.3k
- 441.6k
- 220.8k
- 1226.7k

**Lead rubber bearing (LRB) base isolation:**

- 18” diameter
- Design displacement ~ 10”
- Base shear reduction ~ 58% (Steel), ~ 66% (Concrete)
- Effective stiffness ~ 75 kip/in
- Deflection under wind load ~ 2.1”

**Moat cover**
First floor

<table>
<thead>
<tr>
<th>Concrete Solution</th>
<th>Steel Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>8” Concrete Shear Wall</td>
<td>BRBs</td>
</tr>
<tr>
<td>10”x15” Concrete Beam</td>
<td>W12X87 Beam</td>
</tr>
<tr>
<td>Bamboo Truss</td>
<td></td>
</tr>
<tr>
<td>16”x16” Column</td>
<td>W10X45 Column</td>
</tr>
<tr>
<td>Bamboo beams</td>
<td></td>
</tr>
<tr>
<td>Columns underneath</td>
<td></td>
</tr>
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</table>
Gravity load path
Lateral load path

Steel solution

Concrete solution

Steel bracing

Base isolation

Shear wall

Compression
Tension
MEP design

Nat. ventilation

Central water collection

PV- integrated facade
Climate zones

- Basement
- Ground floor
- First floor

- Natural Vent.: 6'300 sf
- Climatized: 18'500 sf
- Mech. Room: 210 sf / 300 sf
- Vertical Shaft: 2x 80 sf
Distribution tree

Fan-assisted system

Basement
Ground floor
First floor
Floor sandwich

High-tech system
Floor sandwich

Fan-assisted system
Section

Ventilation and water collection
Energy efficiency

PV systems and battery storage

Roof PV systems

TESLA powerpack battery system

Facade integrated PV systems*

Dynamic yearly load simulations**

Table:

<table>
<thead>
<tr>
<th></th>
<th>Yearly PV Production</th>
<th>Total Delivered to Grid</th>
<th>Total Drawn from Grid</th>
<th>Total Operation Emissions</th>
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<tbody>
<tr>
<td></td>
<td>kWh</td>
<td>kWh</td>
<td>kWh</td>
<td>kg CO2 eq</td>
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<tr>
<td>Rainbow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no batteries</td>
<td>266'000</td>
<td>58'000</td>
<td>+28%</td>
<td>3'312'000</td>
</tr>
<tr>
<td>with batteries (270 kW)</td>
<td>266'000</td>
<td>80'000</td>
<td>-280%</td>
<td>910'000</td>
</tr>
<tr>
<td>Movement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no batteries</td>
<td>160'000</td>
<td>51'000</td>
<td>-70%</td>
<td>4'342'000</td>
</tr>
<tr>
<td>with batteries (200 kW)</td>
<td>160'000</td>
<td>30'000</td>
<td>-28%</td>
<td>3'484'000</td>
</tr>
</tbody>
</table>

* Inspired by “3for2 Beyond Efficiency” research project
** Source: Solar-battery calculator excel template by john bourcet, IBS integrated design project

2 units (each 3' x 4' x 7') located in mech. room

Graph:

Dynamic yearly load simulations**
### Decision matrix HVAC system

<table>
<thead>
<tr>
<th></th>
<th>High-Tech</th>
<th>Fan-Assisted Comfort</th>
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</thead>
<tbody>
<tr>
<td>Energy Effi.</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Human Comfort</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Design Flexibility</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Initial Costs</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Reliability*</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Space Impact</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Water Usage</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Cond. Risk</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>AEC Integration Potential</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18</strong></td>
<td><strong>23</strong></td>
</tr>
</tbody>
</table>

*High dependance on chilled water*
Site plan - Movement concrete alternative

- Waste/recycling area
- Material laydown
- Toilets
- Site offices
- Parking area
- Equipment parking
- Emergency evacuation

- Mobile crane 80 ft diameter
- Heavy vehicle route
- Lightweight vehicle route

Tire wash
Target Value Design

Movement concrete

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVENT</th>
<th>ESTIMATE</th>
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<td>RS Means Square Foot</td>
<td>$ 5.7 million</td>
<td>$ 5.3 million</td>
</tr>
<tr>
<td>03/08/2020</td>
<td>Quantity Take-off #1</td>
<td>$ 6.1 million</td>
<td>$ 4.9 million</td>
</tr>
</tbody>
</table>
Target Value Design

Movement steel

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVENT</th>
<th>ESTIMATE</th>
<th>DELTA</th>
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</thead>
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<td>$11,000,000</td>
<td>$ -</td>
</tr>
<tr>
<td>02/10/2020</td>
<td>RS Means Square Foot</td>
<td>$5,079,630</td>
<td>$ 5,920,370</td>
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<tr>
<td>03/08/2020</td>
<td>Quantity Take-off #1</td>
<td>$5,687,993</td>
<td>$ 5,312,007</td>
</tr>
</tbody>
</table>

**TVD - TRACKING TARGET OVER TIME**

**TVD - TARGETS BY CLUSTER**

- **Target**
- **Estimated**
- **Delta**
Target Value Design

Comparison

Estimated Quantity Reliability
- HIGH 35.0%
- MEDIUM 45.0%
- LOW 20.0%

Estimated Cost Reliability
- HIGH 20.0%
- MEDIUM 30.0%
- LOW 50.0%

Estimated Overall Reliability
- HIGH 27.5%
- MEDIUM 37.5%
- LOW 35.0%
Construction sequence

Movement

- Zone 1: Instructional labs and small classrooms
- Zone 2: Instructional labs and study spaces
- Zone 3: Auditorium, Café and small classrooms
- Zone 4: Large classrooms and student offices
Schedule timeline

Concrete alternative

Steel alternative
Decision matrix

Individual disciplines

A

Integration with surroundings

Coherence with culture

Spatial utilization

Community integration

Diversity in study spaces

E

Earthquake/Wind Performance

Building Weight

Regularity

Detailing of Connection

M

Energy demand

ARCH/SE integration

Energy production

Water

Social HVAC acceptance

GHG Footprint

C

Cost

Labor Expertise

Material Locality

Schedule

Construction Risks
## Decision matrix

### Summary and decision

<table>
<thead>
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Virtual design and construction

Image courtesy of Integrating Project Delivery, 2017
## Virtual design and construction

### Integrated Concurrent Engineering

#### ISLAND 2020 MEETING ANALYTICS

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#### Targets & Meeting Metrics

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<th>8-Feb</th>
<th>15-Feb</th>
<th>22-Feb</th>
<th>29-Feb</th>
<th>7-Mar</th>
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<td>≥1 # of follow-up items per discipline</td>
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#### Weekly VR Sessions

360°
Virtual design and construction

BIM: Weekly clash controls in VR

Our target

Example courtesy DPR
Team workflow

Source: Renate Fruchter
Lessons learned

ARCH: “Sometimes you can’t see the forest for the trees”

SE1: “Simple solutions are the answer for complex problems”

SE2: “Really learn to Trust and Listen!”

MEP: “Always keep the final goal and the bigger picture in mind!”

CM1: “Have an open mind and prepare for change!”

CM2: “Plans will never work exactly but they are the key for progress”
Thank You
Appendix
Footprint placement

Solar Optimization

CFD Analysis

$V_{\text{wind}} = 4 \text{ m/s}$
## Virtual design and construction

**PPM: Project production management**

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Targets</th>
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<tr>
<td>Percent plan complete on pull plan %</td>
<td>100%</td>
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<td># of times pull planning is updated per week</td>
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<tr>
<td>RFI Latency</td>
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