Some context

Life on planet Arup
Improving construction productivity

By Elipo Darbosa, Jan Mischke, and Matthew Parsons

McKinsey research finds seven levers can fix construction’s productivity problem, but they require a new approach from all players. We heard from industry leaders about which barriers to change are most likely to fall first.

The McKinsey Global Institute (MGI’s) Reinvesting construction: A route to higher productivity report, released in February 2017, found that the construction industry has an intractable productivity problem. While sectors such as retail and manufacturing have reinvented themselves, construction seems stuck in a time warp. Global labor-productivity growth in construction has averaged only 1 percent a year over the past two decades, compared with growth of 2.8 percent for the total world economy and 3.6 percent in manufacturing (exhibit).
Real gross value added per hour worked, index of 2005 $: 100 = 1995

Source: GGCD-10; national statistical agencies of Turkey, Malaysia, and Singapore; OECD, Rosstat; US Bureau of Economic Affairs; US Bureau of Labor Statistics; WIOD; World Bank; McKinsey Global Institute analysis

Productivity gap = $1.63 trillion

Economic value lost as a result of the gap,\(^2\) by region, $ trillion

Average value added by employees per hour worked\(^1\)

\(^1\)2015 data in real 2005 dollars.
\(^2\)Assumes construction productivity catches up with total economy productivity and current workers are reemployed at the total economy productivity rate.

McKinsey & Company
The industry needs to change; here’s how to manage it.

The construction industry is ripe for disruption. Large projects across asset classes typically take 20 percent longer to finish than scheduled and are up to 80 percent over budget (Exhibit 1). Construction productivity has actually declined in some markets since the 1990s (Exhibit 2); financial returns for contractors are often relatively low—and volatile.
<table>
<thead>
<tr>
<th>Sector</th>
<th>Assets</th>
<th>Usage</th>
<th>Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICT²</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Media</td>
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<td></td>
<td></td>
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<tr>
<td>Professional services</td>
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<tr>
<td>Finance and insurance</td>
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<tr>
<td>Wholesale trade</td>
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<td>Advanced manufacturing</td>
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<td>Oil and gas</td>
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<td>Utilities</td>
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<td>Chemicals and pharmaceuticals</td>
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<td>Basic goods manufacturing</td>
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<td>Mining</td>
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<td>Real estate</td>
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<tr>
<td>Transportation and warehousing</td>
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<tr>
<td>Education</td>
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<tr>
<td>Retail trade</td>
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<tr>
<td>Entertainment and recreation</td>
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<td>Personal and local services</td>
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<td>Government</td>
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<td>Hospitality</td>
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<td></td>
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<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture and hunting</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Based on a set of metrics to assess digitization of assets (8 metrics), usage (11 metrics), and labor (8 metrics).
²Information and communications technology.

Source: AppBrain; Bluewolf; Computer Economics; eMarketer; Gartner; IDC Research; LiveChat; US Bureau of Economic Analysis; US Bureau of Labor Statistics; US Census Bureau; McKinsey Global Institute analysis

McKinsey & Company
Some things are very hard and demand new approaches.
We can make them practical and achievable
But what about the things that we can already do?

Child’s play  Manageable  Impossible
Because there are a lot of those?

Child’s play  Manageable  Impossible
How easy can we make them?

Child’s play  Manageable  Impossible
Current practice
And why we want to change it...
Spreadsheets

Data. Output.

- Calculations
- Specifications
- Drawings
So much data...
So many places!
Spreadsheets

Data. Output.

Where does the data go after this?
Spreadsheets

Messy data that goes nowhere.

Is this really what we want?
Not.
Not. Even.
Technology advances

So should we...
“It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change.”

- Charles Darwin.
“So why do we insist on doing things the ‘old’ way?”

- Us.
WHAT IF...
Creating
A toolmakers mentality...
“The point is that I don't design stuff for myself. I'm a toolmaker. I design things that other people want to use.”

- Robert Moog.
Spreadsheets
Messy data that goes nowhere.

Is this really what we want?
“Why don’t we use the data where it is hosted?”

- Us.
A single data environment
Embedded parameters for intelligent delivery
A single digital tool
Read and write parameters for integrated calculation
Libraries written by other people
Parametric spaghetti
Useful tools

We made some...
Riyadh Metro Project
Package 1
WP12 Deep Stations
Spreadsheet Verification Report - Structures

Document No. M-BAR-000D50-CB00-ECA-000008
Document Status: For Review

<table>
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<tr>
<th>Submittal History</th>
<th>Doc Status</th>
<th>Prepared (Sub-Contractor)</th>
<th>Checked (Sub-Contractor)</th>
<th>Approved (Sub-Contractor)</th>
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<tr>
<td>Rev. Date: 12-JUN-17</td>
<td>Information</td>
<td>Arif T. Kishore</td>
<td>Tim Worland</td>
<td>John Batchelor</td>
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Note: All changes from the previous revision have a line to the left of the text.

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<th>Name:</th>
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<tr>
<td>B - Reviewed with comments: Revise and resubmit; Work may proceed subject to incorporation of comments</td>
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<tr>
<td>C - Objection - Revise and resubmit; Work may not proceed</td>
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<tr>
<td>D - Rejected</td>
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<tr>
<td>E - Review not required: Work may proceed</td>
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<td></td>
</tr>
</tbody>
</table>

Printed: 1 Aug. 17

© 2013 High Commission for the Development of Riyadh
Electronic documents once printed, are uncontrolled and may become outdated. Refer to Appendix for current revision.
Error prone
Difficult to review
Never re-used
Your scientists were so preoccupied with whether or not they could that they didn't stop to think if they should.
Change can be an issue
Fast learns, slow remembers.
Tooling
Patterns
People
Documentation
Governance
Foundations
Rate of change

Software

Hardware
Code the calculations
Easy to read...
Honestly
Write unit tests
Centralise your versioning and quality control
No fear of losing your work
But how do you feed it information?
Useful tools
We made some...
Arup Cardiff
“Hello!”

“I’ve got a calculation problem”

“We’ve got a data problem”

“Ah-ha!”
Connect it all together
We built an engine
That could be built around
Let's be disruptive

So we tried it...
My first parametric truss
“Yeah, yeah – but what about the real stuff?”

- Everyone we work with.
Ok, ok, we’ll take on something “real” then...
Leaving our comfort zone...

**Hand crafted**
*Engineering the products one at a time*

**Mass bespoke**
The model for how we need to be consistently working

**Mass production**
*Engineering the process that creates the products*
Start with the hard problems
Why are they so complex?
Standard design?
“Let’s change that!”

- Us.
We obtained funds...
...and built a team

**The Investors**

A wealth of experience

*And very open minds*

**The Innovators**

Two people with a big idea

*And a lot of coffee*

**The Integrators**

Digital natives

*Impossible is not in their vocabulary*
We mapped current methods...
..highlighted the pain points...
and made improvements...
Creating flow
Create

Follow the value
Eliminate the waste

Process

Deliver
We planned for a successful outcome

<table>
<thead>
<tr>
<th>MUST</th>
<th>SHOULD</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Implement SGN 09 checks</td>
<td>• Alert the user if requirements for “infinite” concrete are not met (plus any other assumptions)</td>
</tr>
<tr>
<td>• Shear only</td>
<td>• Resolve Axial load, moment, minor axis forces</td>
</tr>
<tr>
<td>• “Infinite” concrete</td>
<td>• X by Y arrangement of bars / studs</td>
</tr>
<tr>
<td>• Two columns on studs / bars</td>
<td>• Variable number of top / bottom rows are bars</td>
</tr>
<tr>
<td>• Top x rows are bars</td>
<td>• Revit object for plate</td>
</tr>
<tr>
<td>• Revit object for plate</td>
<td>• Include basic clash checks for “thin” concrete (i.e. can the bent bars fit in)</td>
</tr>
<tr>
<td>• Fin plate centred on plate</td>
<td>• Usage tracking</td>
</tr>
<tr>
<td>• Extensible for other codes</td>
<td></td>
</tr>
<tr>
<td>▪ Alert the user when design assumptions aren’t valid</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COULD</th>
<th>(First Version) WON’T</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Arbitrary substitution of studs for bars</td>
<td>• Design for hanger bars if there is an opening below</td>
</tr>
<tr>
<td>▪ <strong>Moment</strong></td>
<td>• Web interface</td>
</tr>
<tr>
<td>• Capacity reduction adjacent to edges / openings</td>
<td>• Auto size</td>
</tr>
<tr>
<td>• Work for “thin” concrete i.e. plate through to other side of section</td>
<td>• Non-fin plate connections</td>
</tr>
<tr>
<td>• Other bar arrangements (hook-up, hook-side, studs only)</td>
<td></td>
</tr>
<tr>
<td>▪ <strong>Use green book method for plate sizing</strong></td>
<td></td>
</tr>
<tr>
<td>▪ Template Revit checking views (governed by studs, governed by punching etc.)</td>
<td></td>
</tr>
</tbody>
</table>
We developed our processing machine
Left our comfort zone...

Hand crafted
Engineering the products one at a time

Mass bespoke
The model for how we need to be consistently working

Mass production
Engineering the process that creates the products
**STEP 1 RESISTANCES OF BOLT ROWS IN THE TENSION ZONE**

**RESISTANCES OF T-STUBS**

The resistances of the equivalent T-stubs are evaluated separately for the end plate and the column flange. The resistances are calculated for three possible modes of failure. The resistance is taken as the minimum of the values for the three modes.

The design resistance of the T-stub Flange, for each of the modes, is given below:

**Mode 1 Complete Flange Yielding**

Using Method 2: in Table 6.2 of BS EN 1993-1-8:

\[ P_{1,1M} = 8 + 2m \cdot |\Delta M_{1,1M}| \]

\[ P_{1,2M} = f_{y} \cdot A_{b1} \]

modes: 1, 2, and 3.

\[ P_{1,3M} = f_{y} \cdot A_{b1} \]

where:

- \( M_{1,1M} \) and \( M_{1,2M} \) are the plastic resistance moments of the equivalent T-stubs for Modes 1 and 2, given by:
  - \( M_{1,1M} = 0.55f_{y} \cdot t_{b1} \cdot \frac{1}{3} \cdot f_{y} \cdot A_{b1} \)
  - \( M_{1,2M} = 0.55f_{y} \cdot t_{b1} \cdot f_{y} \cdot A_{b1} \)

\( f_{y,1} \) is the effective length of the equivalent T-stub for Mode 1, taken as the lesser of \( f_{y,1} \) and \( f_{y,2} \) (see Table 2.2 for effective lengths for individual rows and Table 2.3 for groups of rows).

\( f_{y,2} \) is the effective length of the equivalent T-stub for Mode 2, taken as \( f_{y,2} \) (see Table 2.2 for effective lengths for individual rows and Table 2.3 for groups of rows).

**Mode 2 Bolt Failure with Flange Yielding**

\[ P_{1,2M} = 2m \cdot f_{y} \cdot A_{b1} \]

\[ P_{1,3M} = f_{y} \cdot A_{b1} \]

\[ P_{1,4M} = f_{y} \cdot A_{b1} \]

where:

- \( P_{1,2M} \) is the yield strength of the T-stub flange (\( f_{y} \) of the column or end plate)
- \( A_{b1} \) is the total tensile resistance for the bolt in the T-stub (\( P_{1,2M} \) for a single row)
- \( n_{b1} = \frac{d_{b1}}{d_{b}} \)
- \( d_{b1} \) is the diameter of the washer or the width across the plates of the bolt head, as relevant
- \( d_{b} \) is defined in Figure 2.5
- \( m \) is the minimum of:
  - \( e_{b} \) (edge distance of the column flange)
  - \( e_{b} \) (edge distance of the end plate)
- \( t_{1,2M} \) is 1.25m for end plate or column flange, as appropriate.

**Mode 3 Bolt Failure**

\[ P_{1,3M} = \sum f_{b1} \]

\[ P_{1,4M} = f_{y} \cdot A_{b1} \]

where:

- \( f_{b1} \) are the plastic resistance moments of the equivalent T-stubs for Modes 1 and 2, given by:
  - \( f_{b1} = 0.55f_{y} \cdot t_{b1} \cdot \frac{1}{3} \cdot f_{y} \cdot A_{b1} \)
  - \( f_{b1} = 0.55f_{y} \cdot t_{b1} \cdot f_{y} \cdot A_{b1} \)

**STEP 1A T-STUB FLANGE IN BENDING**

**Table 2.2 Effective lengths \( f_{y,1} \) for equivalent T-stubs for bolt row acting alone**

(a) Pair of bolts in an unstiffened end plate extension

Note: Use \( m \) in place of \( m \) and \( e_{b} \) in place of \( e \) in the expressions for \( P_{1,2M} \) and \( P_{1,3M} \).

**Circular patterns**

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Yielding</th>
<th>Non-circular patterns</th>
<th>Double curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Individual and yielding | \( f_{y,1} = 2m + 2e_{b} \) |
| Individual end yielding | \( f_{y,1} = 4m + 1.25e_{b} \) |
| Circular group yielding | \( f_{y,1} = 2m + e_{b} \) |
| Corner yielding | \( f_{y,1} = 2m + 0.625e_{b} \) |

Group end yielding

(b) Pair of bolts at end of column or on a stiffened end plate extension

Note: The expressions below may also be used for a column without a stiffener except that the corner-yielding pattern is not applicable.

**Circular patterns**

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Non-circular patterns</th>
<th>Corner yielding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Individual and yielding | \( f_{y,1} = 2m \) |
| Individual end yielding | \( f_{y,1} = 4m + 1.25e_{b} \) |
| Corner yielding | \( f_{y,1} = 2m + 0.625e_{b} \) |

See Notes on page 14.
Coded the calculations
Compiled the calculation library.
Parametric spaghetti
Removed external libraries...

class Element:
    def __init__(self, id):
        self.id = id

def get_id(self):
    return self.id

class Beam(Element):
    def __init__(self, id):
        super().__init__()

class Shell(Element):
    def __init__(self, id):
        super().__init__()

beam = Beam(1)
beam.get_id()
shell.get_id()
For simple mass roll-out
Revit parameters used to drive the process:

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection_End_1_Type</td>
<td>String</td>
<td>Tag with “CIP” to activate Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Connection_End_2_Type</td>
<td>String</td>
<td>Tag with “CIP” to activate Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Connection_End_1_Shear_Vs_Major</td>
<td>Number</td>
<td>Vertical shear input to Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Connection_End_2_Shear_Vs_Major</td>
<td>Number</td>
<td>Vertical shear input to Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Reinforcement_Bars_Diameter_F1</td>
<td>Number</td>
<td>Wall rebar input to Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Reinforcement_Bars_Diameter_F2</td>
<td>Number</td>
<td>Wall rebar input to Dynamo</td>
<td>Standard template parameter</td>
</tr>
<tr>
<td>Reinforcement_Bars_Spacing_F1</td>
<td>Number</td>
<td>Wall rebar input to Dynamo</td>
<td>Standard template parameter</td>
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<tr>
<td>Reinforcement_Bars_Spacing_F2</td>
<td>Number</td>
<td>Wall rebar input to Dynamo</td>
<td>Standard template parameter</td>
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<tr>
<td>Reinforcement_Cover_Far_Face</td>
<td>Number</td>
<td>Wall rebar input to Dynamo</td>
<td>Standard template parameter</td>
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<tr>
<td>Specification_Material_Strenth_Grade</td>
<td>Number</td>
<td>Wall concrete strength to Dynamo</td>
<td>Standard template parameter</td>
</tr>
</tbody>
</table>

Create the digital object
Document everything (especially the bits that don’t work)

Bearing of plate on concrete

The general model has been to consider a cast-in-plate similarly to a base plate. With a typical column base plate a moment is resisted into a concentrated push-pull in the flanges of the column section. However, a cast plate is likely to induce a more even distribution of stress. This aspect has not been implemented due to time & budget constraints.

“I would follow your alternative treatment, considering the concrete behind the cast-in-plate similarly to how you would consider a normal reinforced concrete section. Providing the limiting strain (usually 0.0035) can be met, the rectangular stress block, starting at a distance from the neutral axis, results in a force and moment very similar to those from a realistic stress-strain relation; only if there were brittle components in the system (for example, some form of brittle shear stud) would this be inappropriate.”  - Ian Feltham 07/2017

Bottom node of strut and tie diagram

There is limited guidance on how to dimension the CCC node at the base of the cast in plate. Under guidance from Ian Feltham, for this project the height of the node has been taken equal to the depth of the compression block and the width has been taken as the minimum of the compression block width, or the stud spacing + z (i.e. assuming a 30-degree spread of stress).

Following these recommendations has led to the CCC node failing at very low loads. The design of this CCC node will require additional review.

Shear stud interaction

SGN 09 does not provide guidance on how shear studs interact, and so there are no limitations on closely spaced shear studs beyond trying to adhere to good practice. More guidance would be welcomed to allow a tool to inform a user of poor spacings.

Stress block relative to fin plate

Current guidance does not relate compression block position to the fin plate, but to the bottom edge of the plate. In extreme cases where the plate extends a long way from the bottom of the fin plate the plate would clearly be too flexible for this diagram to form. Additional guidance is required.

Strut and tie diagram / additional links

Current practice is generally to avoid introducing additional links behind the cast in plate, however the guidance suggests that for cot(θ) > 1.5 links are required to form a modified strut and tie diagram. Current guidance suggests that the bearing stress block grows from the base of the cast in plate, leading to high strut angles and thus requiring links behind the plate.

As deep plates are often required to allow more shear studs to be introduced an alternative could be that the strut initially forms at a desirable / low energy angle with the plate forming a compression block that grows from nearer the middle of the plate. Only for higher loads on a given plate arrangement would the modified strut and tie diagram be required. Clearly this approach would result in higher forces in the anchorage bars than for a deeper ‘Z’, and so the engineer would need to choose between having larger anchorage bars or introducing additional links.

Further research would be required to guide a logical approach to the strut & tie diagram and stress block locations.

Axial force in wall

Impact of axial force in the wall is not addressed in guidance.
DesignCheck - Cast In Plates

Background
The DesignCheck framework is a vision of the digital future of structural engineering. The aim is to create an ecosystem of design tools for 'stand-alone' structural components that combines detailed and verified engineering calculations with simple user interaction through a variety of software platforms.

The fundamental basis is the creation of a centralised repository of code based design checking calculations that plug into a local users automated workflow. This could be Grasshopper and Dynamo based, or through more direct pure coding approaches. The work documented here represents the first step in building this framework using the practical example of cast-in plate connections through Dynamo in a structural Revit model.

IAA 17006: http://invest.intranet.arup.com/lay out=projsheet&pro jid =17006&tab=projsheetdetailstbpage0
DesignCheck community site: https://arup.sharepoint.com/sites/community-digital-design/designcheck

Process
This tool has been developed around a defined workflow that is inherent in the operation of the tool. The archimate process map below (and downloadable further down this page) documents the steps required for successful execution of the tool and indicates the required inputs and outputs.
Showcase it
“What can we do with the model output?”

- Everyone we work with.
Review the model
Review the output text
Review the metrics.
Digital production

Modelling for success
AM I THE ONLY ONE AROUND HERE

WHO DOESNT OVERRIDE DIMENSIONS?!
A model first approach
Everything IN | Everything OUT
A single source of the truth

No more ‘double handing’ of data
Design

Everything the client needs
Manual data **transfer** between two process streams 😞

- Analysis and design
- Production and drawing

Data transfer between two process streams.
No data transfer in one flowing process stream

Analysis, design, production and drawing
Direct experience
1-Click virtual reality
Spot what ‘looks wrong’
Making time for thinking things through

¡YAY!
Improving
Adding to our engine
“This couldn’t get any better”

-Us
“Yeah it could”

Matteo Cominetti - People
Senior Programmer
Digital Technology, London Office

...get an Arup photo Matteo!
Version 2 API

Engineers, Architects, Technicians

Script (C#, VB.NET, Python...)

- Web Browser
- Code
- Excel
- Revit
- Grasshopper
- Dynamo
select a calculation to start
The future
What’s next?
Speckle integration?
Changes to geometry pushed to stream

Speckle calls ArupCompute
API with updated inputs

ArupCompute uses DesignCheck to
perform engineering calculations

Results sent back to Speckle

Stream updated with results
Data harvesting
To conclude

If you only remember one bit
Comprehensive and complete 3D modelling

Complete accuracy and embedded information

Better insight to improve our design and delivery
Use a single data environment to exercise control

Build and enhance digital toolsets that work for us

Improve our processes and embrace automation
We took our engine...
...and built our process around it
“A late change in requirements is a competitive advantage.”

- Mary Poppendieck.
Design automation
Dynamo for Engineers, Design for All
Processes that work for us

Ian Wise | Senior Engineer | Arup
Steven Brown | Engineer | Arup
Hugh Groves | Engineer | Arup