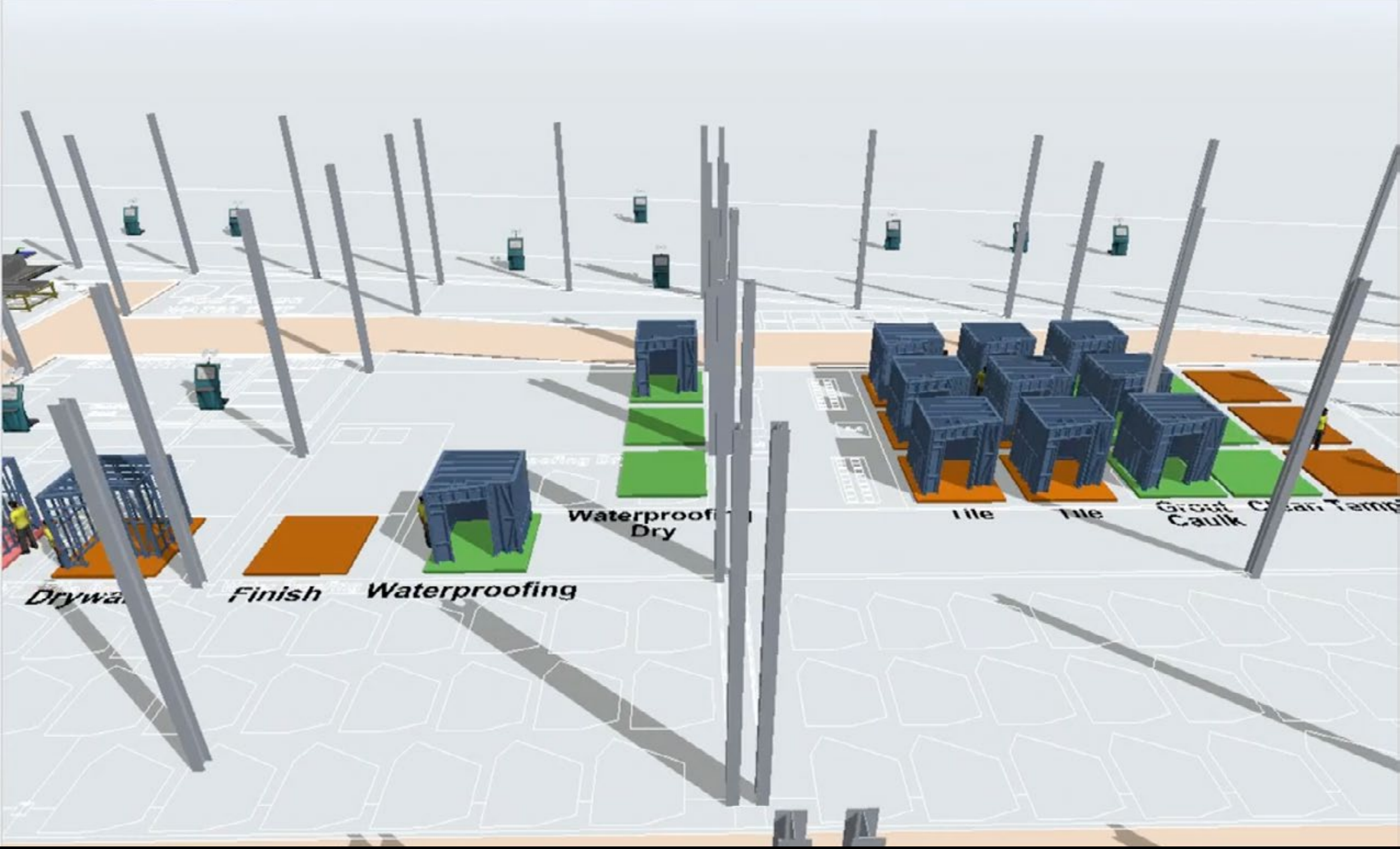



BUILDING. REDEFINED.

# UNLEASHING THE POWER OF PROCESS ENGINEERING AND DISCRETE-EVENT SIMULATION TO OPTIMIZE MULTI-TRADE PREFABRICATION

## EASLEY & RIVERS | A CASE STUDY

# INTRODUCTION

### WHAT IS DISCRETE-EVENT SIMULATION (DES)?

DES is a way to model and predict how a system will react to events by adjusting variables. DES models system behavior and performance by depicting it as a series of events happening at discrete points in time. DES can help you understand and improve work by making it easy to see impacts. This tool drives process improvement and data-driven decisions across many industries including manufacturing, healthcare, warehousing, material handling, supply chain, and airports.

### WHY USE IT IN CONSTRUCTION?

Construction is a complex system with many "events" (materials arrivals; sequencing prefabricated assemblies, work delays; labor fluctuations; etc.). Superintendents, fabrication plant managers, and process engineers are tasked with the immense challenge of planning and sequencing work to deliver a complicated building assembly over months and years. They are also tasked with reacting to change and mitigating the impacts. DES provides a methodology to see how the system will perform based on their plan, and then allow construction field and fabrication leaders to optimize flow to improve labor utilization and throughput. It enables construction teams (owners, GCs, trade partners) to see the impacts of changes (schedule, material, design) to better predict, plan for, and manage variation.

The ability to predict outcomes, expose risks, and plan to solve problems before they happen can dramatically impact project success, whether in the fabrication environment or the job site. DES is a cost-effective way to test multiple scenarios in a model without the expense of testing/prototyping in the real world.

# CASE STUDY – MULTI-TRADE PREFABRICATION

### BACKGROUND

**Easley & Rivers** (E&R) is a Pittsburgh-based specialty contractor known for its expertise in metal framing, fireproofing, insulation, drywall, plastering, and acoustics. E&R, working as a trade partner for the joint venture of Whiting Turner and PJ Dick, was set to take on the huge challenge of manufacturing 624-bathroom pods at an offsite facility for the University of Pittsburgh Medical Center (UPMC). The team leased a vacant warehouse facility for production and storage. This was E&R's first major project prefabricating this specific type of multi-trade component (bathroom pods) offsite. To offset the steep learning curve, E&R partnered with ICG to support the development and start-up of this near-site production line.

**PROBLEM STATEMENT**

How do we rapidly set up and optimize the manufacturing of 624-bathroom pods at a new, temporary near-site production facility while building new skills in the local workforce, minimizing project risks, meeting our field demand, and increasing profit for the entire team?

Our team was composed of highly skilled, experienced trades with a supportive GC, Owner, and coach in a beautiful facility for production. However, our most significant challenges in addressing this question and fulfilling the potential of offsite manufacturing were:

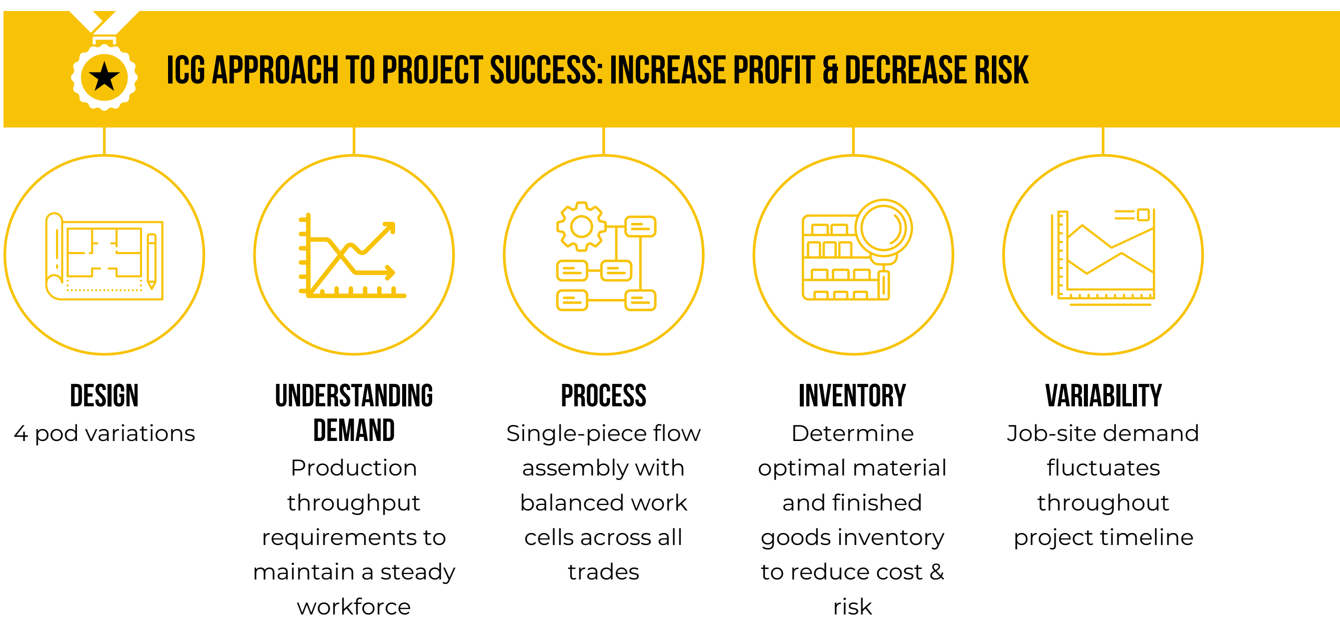
- Aligning trades to operate as a system
- Defining manufacturing scope
- Determining production rates
- Setting inventory targets
- Understanding batch vs. single piece flow as a manufacturing method
- Adapting appropriate manufacturing skills needed

# ICG METHODOLOGY

ICG identified DES as the ideal method and tool to support the team in tackling these challenges.

*Figure 1: ICG Approach*

The visual below summarizes the variables used to optimize the production system.




*Adapted From: Garrett Bryan, Chet Carlson, Stanislav Gaponenko, & and Shubhraneel Mitra, 2023*

**DESIGN**

*Design for Manufacturing and Assembly* (or “design for prefabrication”) is an engineering methodology focusing on optimizing the manufacturing and assembly aspects of a product. It causes us to focus on decreasing and combining steps; standardizing; and reducing the complexity of materials, quantity of parts, etc. to shorten and/or mistake-proof the process. As we shift to thinking about the assembly of buildings as a series of products, we can shape our designs to have a high impact on quality and cost.

In this case, the design had already been established when ICG was brought onto this project. Fortunately, the **HGA** team prioritized optimizing prefabrication from the start of their design process. The team limited bathroom designs for the bed tower to only four options: a left and right standard staff/guest pod, and a left and right patient room pod. This low variability design was ideal for a **single-piece flow** assembly operation, however the team's initial plan was a batch production operation.

### DEMAND STUDY: UNDERSTANDING DEMAND & SETTING DAILY PRODUCTION TARGETS

Demand was based on when the Whiting Turner/PJ Dick Project Superintendent asked for delivery to the jobsite. The planned delivery of pods included 7-15 batches in a single day, with a maximum of 50 pods in a week. Given the common frequency of construction schedule changes, the prefabrication team needed a playbook to respond to field changes while still meeting demand without impacting the steady single-piece flow of assembly.

ICG led the team through a Demand Study process to develop scenarios building this first part of the playbook. The Demand Study helped the team make a data-driven determination of:

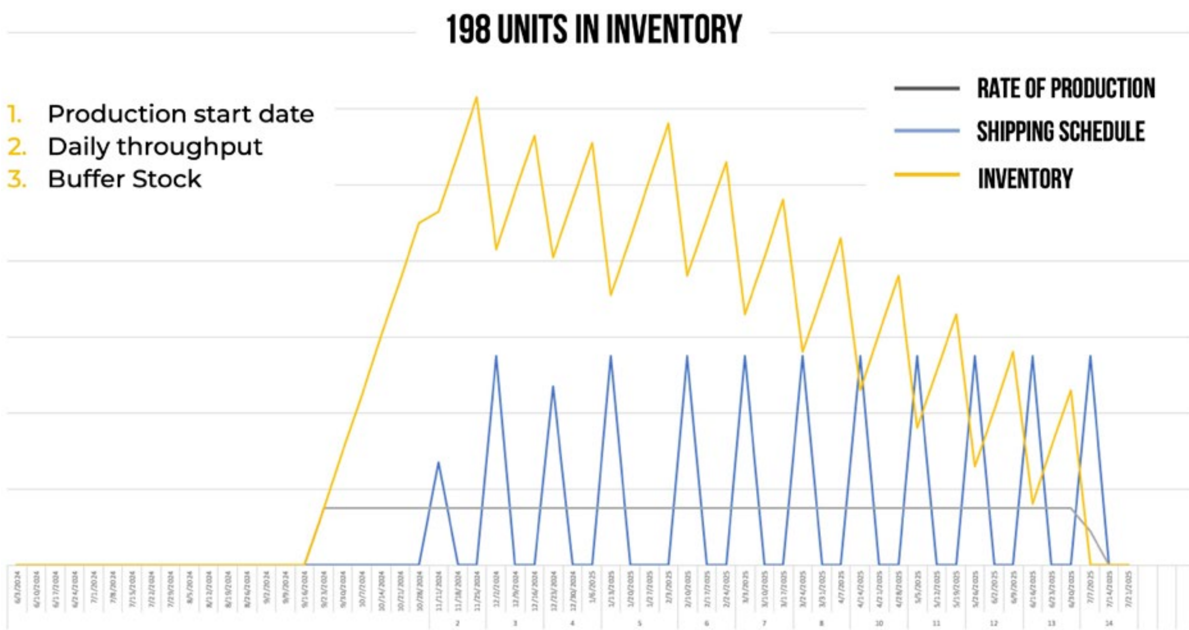
1. When to start production
2. What the ramp-up cadence could be
3. How much inventory to target at any given time during the project; all while meeting the delivery dates
4. Which variables would impact inventory needs without overproducing

To run production planning scenarios, the team had to define all variables that could impact production. Identified known variables were:

- Pod storage capacity onsite and in the facility (the team had limited space)
- Materials delivery schedule (long-time lead items; specialty materials procured from other manufacturers)
- Onsite install schedule (leveraging the traditional construction schedule and the team's early pull plan)
- Delivery amount (e.g. number of pods)

The project team considered production planning scenarios ranging from production of 1-3 pods per shift and varying start dates. The selected scenario would reduce risk to delivery by factoring in a calculated inventory and ramp-up time to establish process stability. The Demand Study model illustrated that inventory would peak at 198 units prior to the first install as seen in the graph on the following page.

*Figure 2: Demand Study*




After completing the Demand Study, daily production targets were established and used to calculate production takt time. **Takt** is a manufacturing term used to determine the cadence (or per unit production rate) each station in a single-piece flow environment must operate to meet demand. The takt time is calculated using the formula below:

*Figure 3: Takt Calculation*

$$\text{TAKT} = \frac{\text{AVAILABLE PRODUCTION TIME}}{\text{CUSTOMER DEMAND}}$$

$$\text{140 MIN.} = \frac{\text{420 AVAILABLE MINUTES}}{\text{3 UNITS (PODS) PER SHIFT}}$$

For this project, it was necessary for the production line to produce a finished bathroom every 140 minutes. Therefore, it was necessary for products to move to the next station on the main production line every 140 minutes.

### UNDERSTANDING & OPTIMIZING INVENTORY

There are numerous tools the ICG team uses to determine optimal inventory. While our team teaches and utilizes lean principles, such as just-in-time (JIT) production, we also believe JIT does not mean zero inventory. Inventory comes at a cost and can add risk, but it can also be strategically used to reduce risk.

The first concept ICG introduced to E&R was a dedicated ramp-up time. Demand for bathroom pods was three per shift, but a ramp up time included one pod per shift for the first two weeks, then two pods per shift for the following two weeks, allowing time to stabilize the process and work out any issues. This approach allowed operators to understand the process, process engineers to confirm cycle times and process balancing, and the design team to confirm the final product falls within tolerances. When startup issues arise, they can generally be resolved without impacting production targets.

Jobsite demand variability is also likely on many projects and taken into consideration when determining proper inventory levels. Safety stock can support demand if the schedule is moved up to a certain level, and storage space is often necessary with installation delays. Both were considered at the production facility to determine optimal inventory levels.

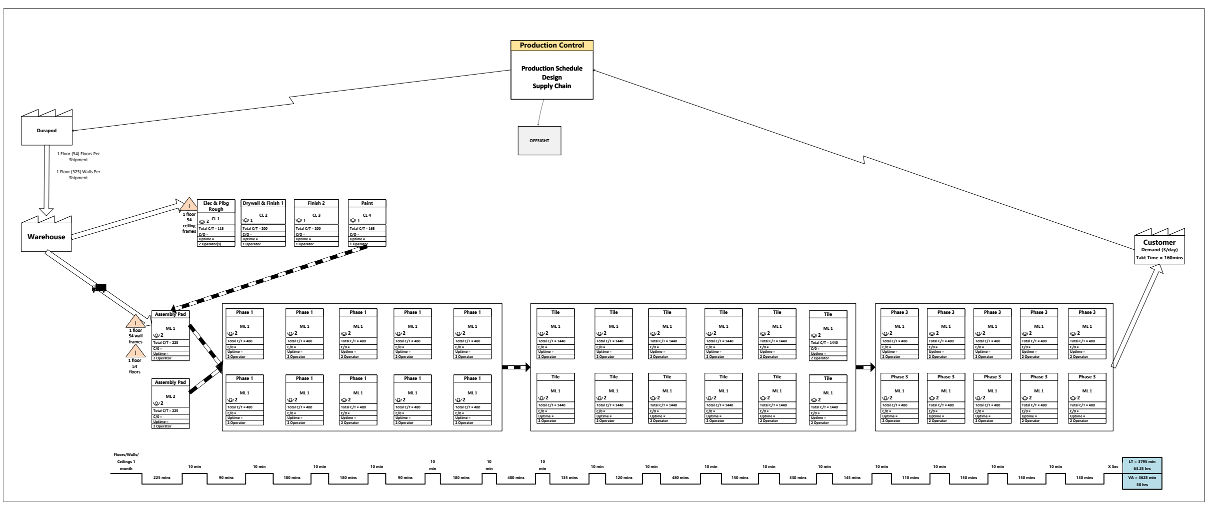
Once an initial inventory plan was developed, the E&R team leveraged Failure Mode Effects Analysis (FMEA) to prioritize risk mitigation. Possible failures included supply chain shortages, installation errors, schedule changes, and logistics complications. Each potential failure was ranked based on severity, likelihood, and detection. Items with the greatest score were prioritized for corrective actions and built-in quality countermeasures, most significant of which was to ensure adequate inventory supported supply chain variability.

## DEFINING AND EVALUATING THE PLANNED PRODUCTION PROCESS

### LEVERAGING DES & STANDARD WORK

Lean thinking and process optimization methods are central to establishing a single-piece flow assembly operation. ICG's first objective was to help the team to clearly understand how work *should* be broken down. The transition from traditional construction methods to construction manufacturing methods required this seasoned team of carpenters, plumbers, and electricians to look at the work differently. This was done through **value stream mapping**, a lean method for visually documenting the flow of information, materials, people, and products from arrival at the production facility through installation in the field. The current state value stream mapping exercise helped this multi-trade team (from different companies) understand each other's workflow and how they fit together in the production system. The value stream map also provided critical inputs required to the setup of the discreet event simulation. Setting up a DES model requires key components, including stations, processes, and operators to be defined. These are the foundations for the object flow diagram for initial model set up.

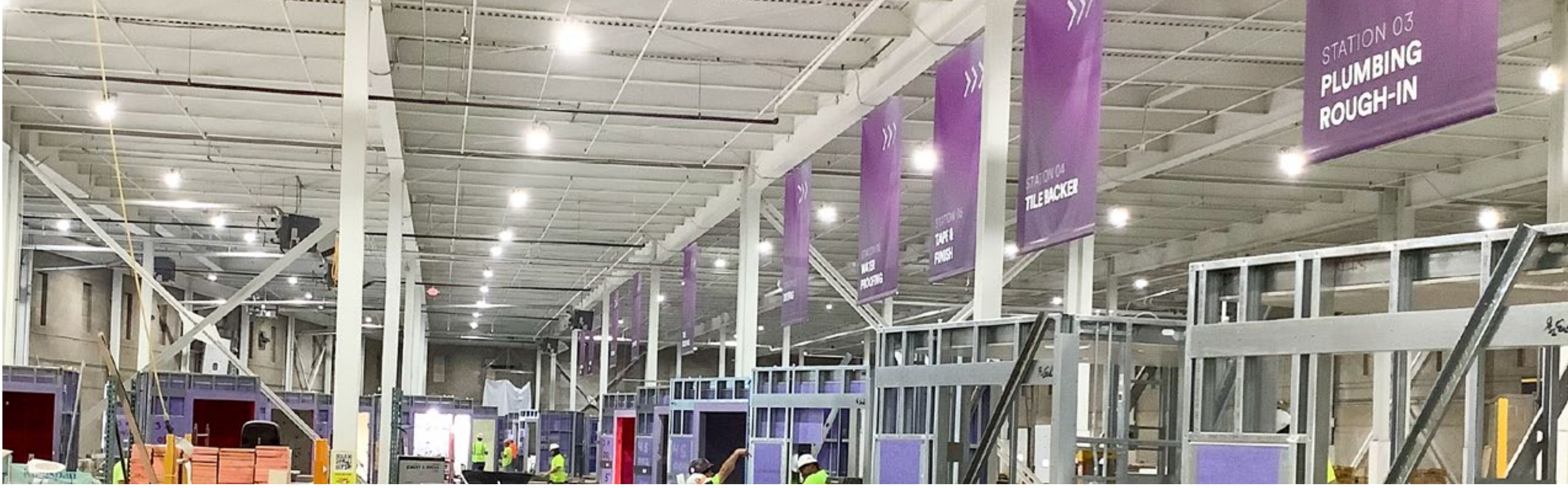
*Figure 4: Current State Value Stream Map*




After documenting initial value stream map, the team worked together to document the pod production line process flow in greater detail using ICG's **Line Sequence and Structure Template**, a form of **Standard Work** detailing how each station is broken down, including:

- Process steps assigned to each station
- Cycle times
- Operator count
- Labor type
- Process owner
- Specialized equipment

The information is key to the setup of the DES model and more importantly, is foundational to process optimization and improvement. This initial line sequence and structure included high-level **cycle time** information. Cycle time is the total time it takes to produce an assembly from start to finish in each state. Because we did not yet have time study data and the line was not operational, cycle time estimates were provided by our craft experts from the field.




Below is an example of a multi-trade Line Sequence and Structure.

*Figure 5: Line Sequence and Structure Template*

**CARSON STREET BATHROOM POD LINE SEQUENCE AND STRUCTURE**

| STATION | NUMBER | TITLE | PROCESS | LABOR TYPE | TIME | AVERAGE | MAX | MIN | EFFICIENCY |
|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Line** | **1** | **Electrical/Plumbing Rough In** | Place finish side up on table | Carpenter | 10 | 84 | 92.4 | 9.45 | 60% |
| | | | Use jig to layout can lights | Electrician | 10 | | | | |
| | | | Place pre-wired housings on ceiling | Electrician | 6 | | | | |
| | | | Secure housings metal frame | Electrician | 6 | | | | |
| | | | Layout plumbing | Plumber | 10 | | | | |
| | | | Support install | Plumber | 12 | | | | |
| | | | Pipe install (DHW, DCW) | Plumber | 15 | | | | |
| | | | Insulate pipe | Plumber | 15 | | | | |
| **Ceiling Line** | 2 | **Install Drywall** | Install drywall | Carpenter | 20 | 30 | 33 | 27 | 21% |
| | | | Tape joints and spot screws | Finisher | 10 | | | | |
| **Ceiling Line** | **3** | **Dry (buffer of 3)** | Dry | | 480 | 480.0 | 528 | 432 | 343% |
| **Ceiling Line** | 4 | **Finish** | Finish Coat | Finisher | 10 | 70.0 | 77 | 63 | 50% |
| | | | Dry | Finisher | 45 | | | | |
| | | | Sand & Wipe down | Finisher | 15 | | | | |
| **Ceiling Line** | **5** | **Paint** | Paint/Prime coat 1 | Finisher | 20 | 110.0 | 121 | 99 | 79% |
| | | | Dry | N/A | 45 | | | | |
| | | | Finish Coat | Finisher | 20 | | | | |
| | | | Dry | N/A | 20 | | | | |
| | | | Move ceiling to staging | Carpenter | 5 | | | | |
| **Main Line** | **1** | **Assembly pad** | Place floor on launch pad | Carpenter | 10 | 105.0 | 115.5 | 94.5 | 75% |
| | | | Floor protection | Carpenter | 10 | | | | |
| | | | Wall Panel install | Carpenter | 30 | | | | |
| | | | Ceiling install | Carpenter | 15 | | | | |
| | | | Install break metal at corners | Carpenter | 20 | | | | |
| | | | Vanity angle support | Carpenter | 10 | | | | |
| | | | Remove from launch pad | Carpenter | 10 | | | | |
| **Main Line** | **2** | **Electrical Rough In** | Electrical layout | Electrician | 15 | | 19.8 | 16.2 | 13% |
| | | | Place prefabricated assemblies | Electrician | 10 | | | | |
| | | | Install pre fabricated assemblies | Electrician | 40 | | | | |
| | | | Install conduit supports | Electrician | 15 | | | | |
| | | | Secure coinduit | Electrician | 10 | 18.0 | | | |

For this multi-trade team from five different companies, the systematic and detailed station documentation, along with the identification of responsible parties, means and methods, and station equipment, proved extremely useful for alignment. Although it was used to assist with line design and setup in this instance, it also proved to be an especially helpful tool for managing changes in products, demand, and labor once up and running. While very typical in manufacturing, ICG has found that the use of this simple but powerful tool is highly uncommon in traditional and prefabrication construction environments.

## MODELING CURRENT STATE PLANNED PRODUCTION IN FLEXSIM

This collection of this initial data completed the information required to set up the base model in FlexSim Our object flow diagram (from the Value Stream Map) and line structure document(above) were used to replicate the **current state** planned multi-trade production system in the FlexSim model environment.

The image below is a simple visual demonstrating how FlexSim works: input variables such as arrival rate of material, process cycle times, labor count, and delays to produce an output of expected throughput, utilization rates, and states of each processor or station throughout the shift.

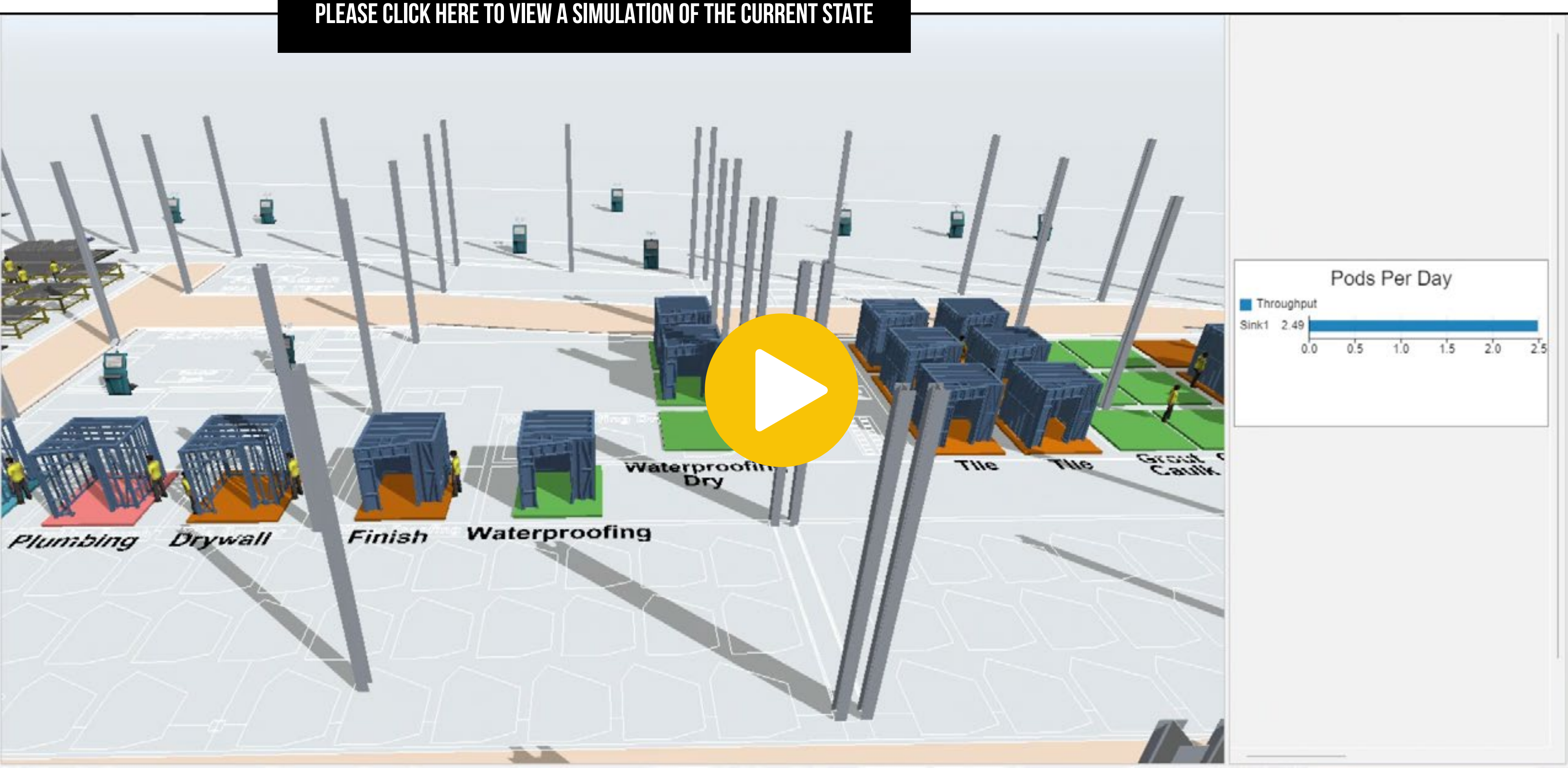

The ICG team ran the model to verify and ensure it was running as intended with station, operator, and cycle time relationships. Once successfully verified, it was time to validate the model with the GC and E&R production team. During this phase, we introduced the model to the operators (carpenters, plumbers, electricians), production facility leadership (Foreman), and the GC project leadership team. The FlexSim model served as a great tool for project stakeholders to visualize what the production line would look like once operations began for both flow of products as well as space utilization.

## DES INITIAL FINDING

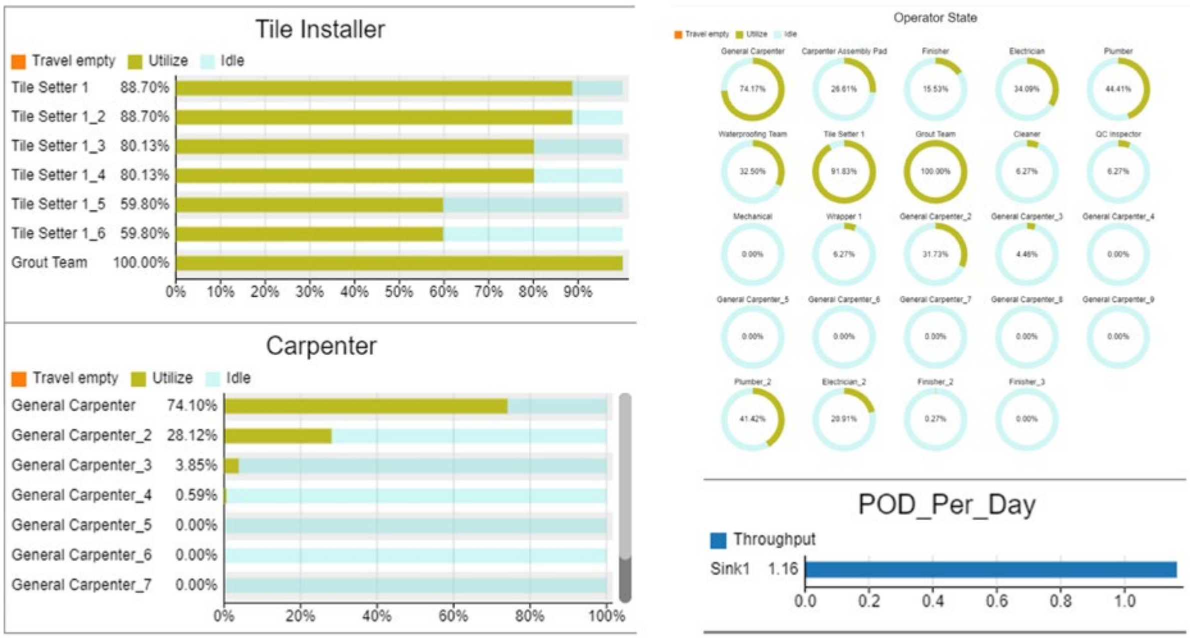
**THE PRODUCTION PLAN AS ENVISIONED WOULD NOT WORK**

**CURRENT STATE**

**PLEASE CLICK HERE TO VIEW A SIMULATION OF THE CURRENT STATE**



The initial model illustrated the team would not meet the daily throughput target. A bottleneck was identified in the tile station, impacting throughput and operator (carpenter labor) utilization. Most of the idle time in the process was due to the waste of waiting on an unbalanced line, creating significant idle time for multiple operators.




The team was able to see and recognize the *batch processing approach was not sufficient to provide required number of pods*. **A change was required and the team was able to leverage DES to test optimization scenarios.** The DES software helped us **see** the pacesetter and bottleneck; we could optimize the whole system by controlling the pacesetter and addressing the bottleneck. The use of DES in production planning is invaluable, the team was able to see the limitations and address them well ahead of scheduled delivery dates.

## OPTIMIZING THE PRODUCTION PROCESS

### LEVERAGING DES & STANDARD WORK

*Standard Work*

Before optimizing process and model optimization scenarios, it was critical to have Standard Work for each station and real cycle time information in hand. Our initial model was based on estimated cycle times from individual workers. These estimates were largely based on "field construction" experience. Before making major adjustments to our means and methods, it was critical to have actual cycle times based on real time studies. ICG led the E&R multi-trade team to develop standard work for each station, including performing **time studies** to confirm cycle times. These updates would replace the initial model estimated cycle time data.

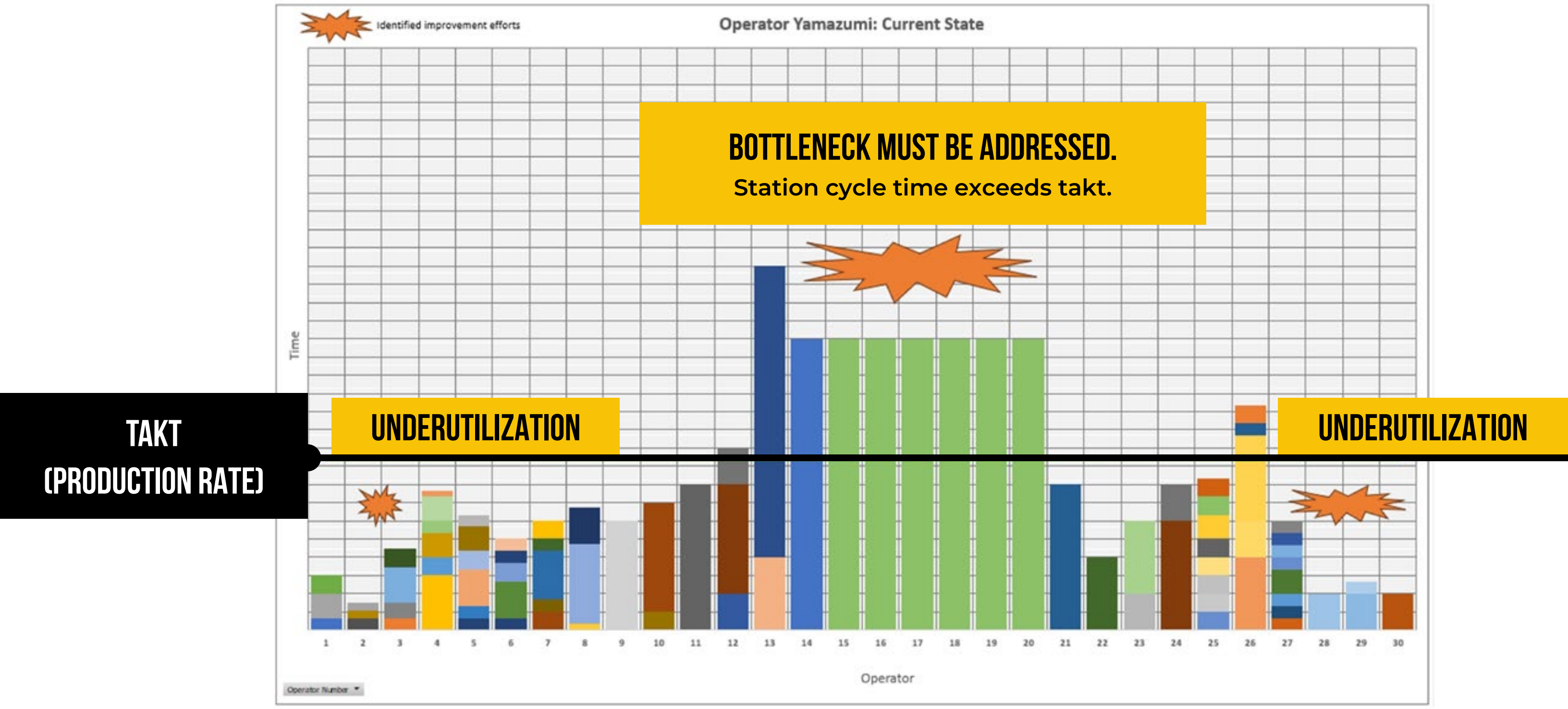
While commonplace in manufacturing, this level of standard work is atypical in construction, especially across a multi-trade/multi-company operation. This is not a small undertaking but adds immense value, enabling the team to balance the process before production ramped up based on actual data. ICG was able to take this data and leverage the model to visualize for the team:

1. Specifically where in the production line constraints and/or bottlenecks existed
2. Where cycle times for certain tasks were above our takt time

It was critical that cycle time remain below the takt rate at each station. In other words, we could not have a single station on the main line operating at >140 minutes, which caused bottlenecks and waste across the system.

With time study data in hand, the team utilized **Yamazumi**, another traditional manufacturing tool for balancing work with many powerful applications in construction to address one of our most regular daily challenges: labor and work balancing on the job site and fabrication facility. The Yamazumi Chart below for the planned production cycle times in the current state shows productivity at each station and compares station work against the necessary takt time established during our Demand Study.

*Figure 6: Yamazumi Chart of Current State Production Plan*



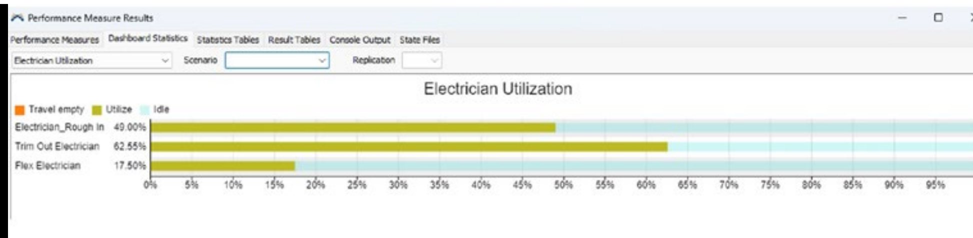

**OPTIMIZATION SCENARIOS LEVERAGING DES**

The team was now able to utilize Discrete-event simulation (in FlexSim) to gain a deeper understanding of how each process impacts the overall system, as well as consider contributing factors to process cycle time variation (e.g. learning curve, interruptions, etc.) before running different experiments to optimize our production system.

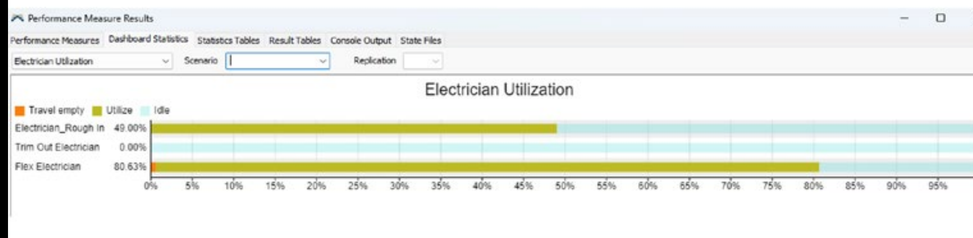
ICG helped the team create experiments with different model parameters. The problem solving toolkit for a construction superintendent and manufacturing Process Engineer have a lot in common. Common solutions to be evaluated would include:

» Adjusting manpower
» Running processes in parallel (process solution)
» Leveraging sub-assemblies (process solution)
» Seeking supplier product innovations and improvements (engineering solution)
» Leveraging automation (engineering solution)

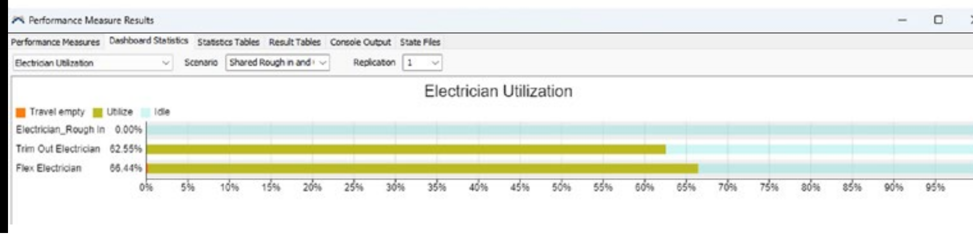
**SCENARIO 1**
Dedicated op for all stations




**SCENARIO 2**
Shared ceiling & trim op




**SCENARIO 3**
Shared ceiling & rough op




The advantage of taking a process engineering approach, enabled by data and the DES model, is the ability for the team to isolate variables and find the optimal solution for the whole system.

Manpower adjustments are the most frequent and first considered solution in construction; DES provides the opportunity to instead consider other options to optimize manpower use. The example at right illustrates DES' power: we were able run three different scenarios to look at optimization of electrical labor, visualizing the impacts of combining and separating tasks across workers. The E&R team ran several scenarios in FlexSim to address the tile station bottleneck. Collectively, ICG and the E&R team identified three possible solutions:

1. Add manpower
2. Parallel processes
3. Create a tile subassembly line

Based on our experience (with tile operations) and the space constraints of the facility, we chose to explore how parallel processes would impact throughput.

## RESULTS

The model illustrated that adjusting the tile process to run 4 stations with 3 lanes in parallel would allow the team to meet the demand of 3 pods per shift. After multiple scenarios were run to find a balance in the line, the results demonstrated opportunity for 3.65 units per day. While this did increase the operator count from 25 to 31, it proved to be the best solution for this multi-trade environment and optimized the labor cost per unit.

The ability to run scenarios provided valuable information to the team and removed risk in running scenarios with the actual system. By adding just 5 operators and reconfiguring the process expected production was improved by 2.36 units per day and enabled the team to meet the UPMC demand.

*Future State*

Future state throughput was achieved by optimizing labor and addressing the tile bottleneck by running parallel processes.

**PLEASE CLICK HERE TO VIEW A SIMULATION OF THE FUTURE STATE**

# IN CONCLUSION

Through the application of lean principles, manufacturing methods, and the use of Discreet Event Simulation, the E&R team ultimately:

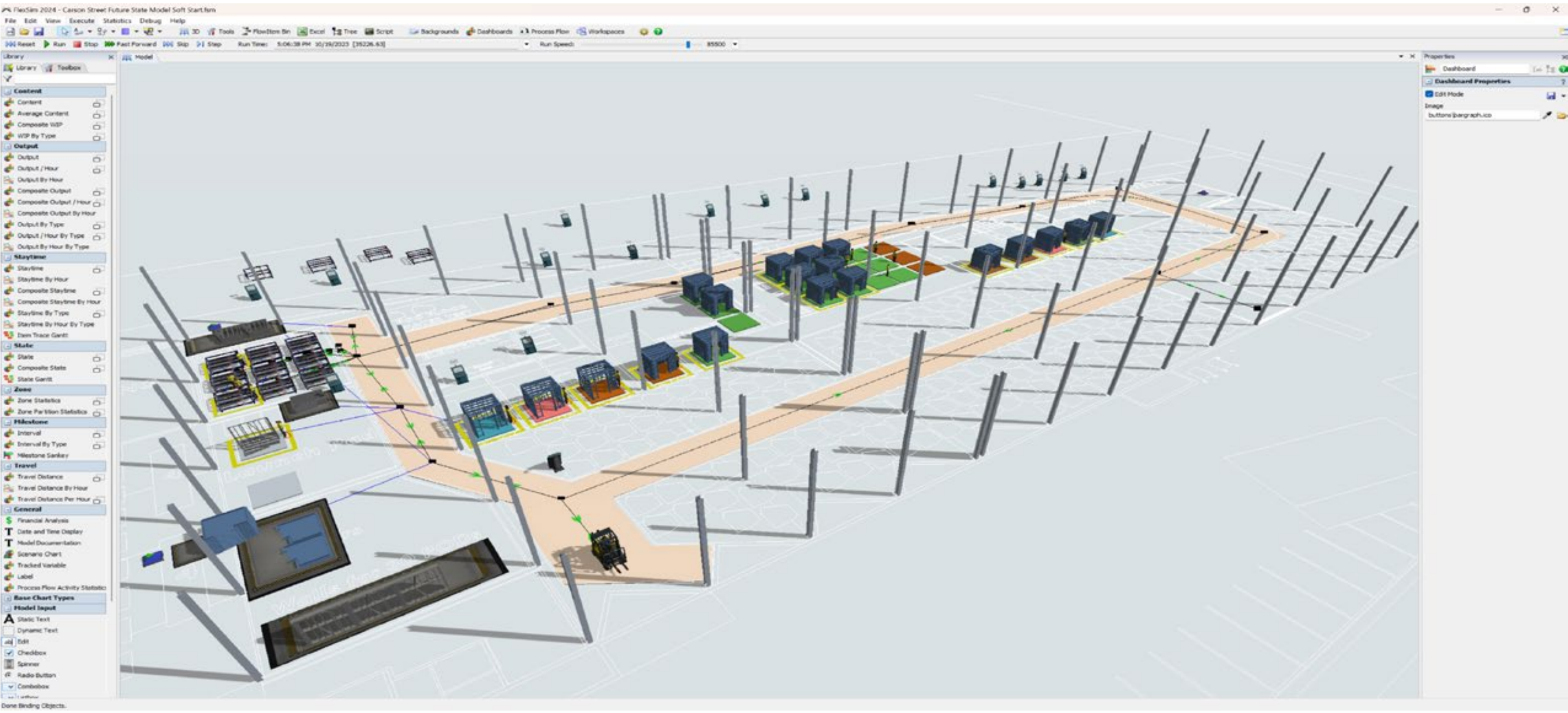
- Applied single piece flow to the production process
- Balanced each station
- Produced with all cycle times below the Takt
- Most importantly, met the throughput target

By rethinking the process, and not building too far ahead (as initially planned), the team also made dramatic labor savings (even with added station manpower) by starting production more than four months later than initially planned.

The business results speak for themselves:

| | **ORIGINAL PLAN** Batch | **FUTURE STATE** Single Piece Flow | **PAYOFF** |
|---|---|---|---|
| **Pods per day** | 1 | 3 | **3X PRODUCTION** **53% LESS LABOR** **$4M PREDICTED SAVINGS** |
| **Labor hours per pod** | 156 | 73 | |
| **Total labor hours** | 100,000 | 46,000 | |
| **Total labor cost** | $7.5 million | $3.5 million | |
| | **CONSTRUCTION MINDSET** | **MANUFACTURING MINDSET** | |

The use of FlexSim and DES, especially, provided excellent value to E&R and this project. It proved process feasibility and exposed risk prior to startup while enabling the right countermeasures to be selected based on data. For the E&R team, these new methods and approaches to project planning and problem solving have set them on a new path towards industrialized construction excellence and ongoing work in this space.



# GLOSSARY OF TERMS

**Single-piece flow**: a lean manufacturing technique involving producing products one at a time rather than in batches.

**Takt**: a manufacturing term used to determine the cadence (or per unit production rate) each station in a single-piece flow environment must operate to meet demand.

**Value stream mapping**: a lean method for visually documenting the flow of information, materials, people, and products from arrival at the production facility through installation in field.

**Time studies**: a study used to understand process duration and operator utilization

**Yamazumi**: a tool aiding in the visualization of bottlenecks and overworked operators or processes

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# ABOUT THE AUTHORS

**ICG**

**Industrialized Construction Group (ICG)** is the team that developed and maintains the **Industrialized Construction Maturity Assessment$^{SM}$ (ICMA$^{SM}$)**, a robust, data-driven performance assessment and customizable standard to help determine how your organization stacks up in industrialized construction and how to achieve your business goals faster. As companies were being assessed across the 70 topics contained within the ICMASM, the data began to show common gaps in maturity in the industry, largely in the **disciplines of Manufacturing and Continuous Improvement**. ICG developed the Construction Manufacturing System to support organizations in their growth and learning new foundational skills to accelerate prefabrication success. How can we advance prefabrication **capabilities** in the construction industry to benefit from lean **manufacturing methods** like many industries before us? One way is to utilize DES to predict outcomes, ultimately reducing risk in making data-driven decisions.


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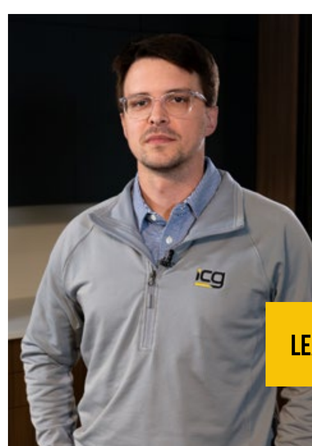
**STEPHEN HAYES**
INDUSTRIAL ENGINEER

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