Optimizing the Flow of Work & Workers: Investigating a Systematic Approach to Unlocking Productivity in Manufacturing

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Abstract

Frontline leaders in many types of discrete manufacturing and aftermarket operations must determine "how to staff the line" at the start of a shift. Today, they typically use a combination of whiteboards, spreadsheets, and personal intuition. This whitepaper investigates an opportunity to improve the productivity of a manufacturing operation by up to 15% – as measured by Throughput – by leveraging machine learning (ML) and artificial intelligence (AI) to optimize the flow of work and workers on the shop floor.

This initiative is a work-in-progress, and we appreciate feedback: info@covalentnetworks.com

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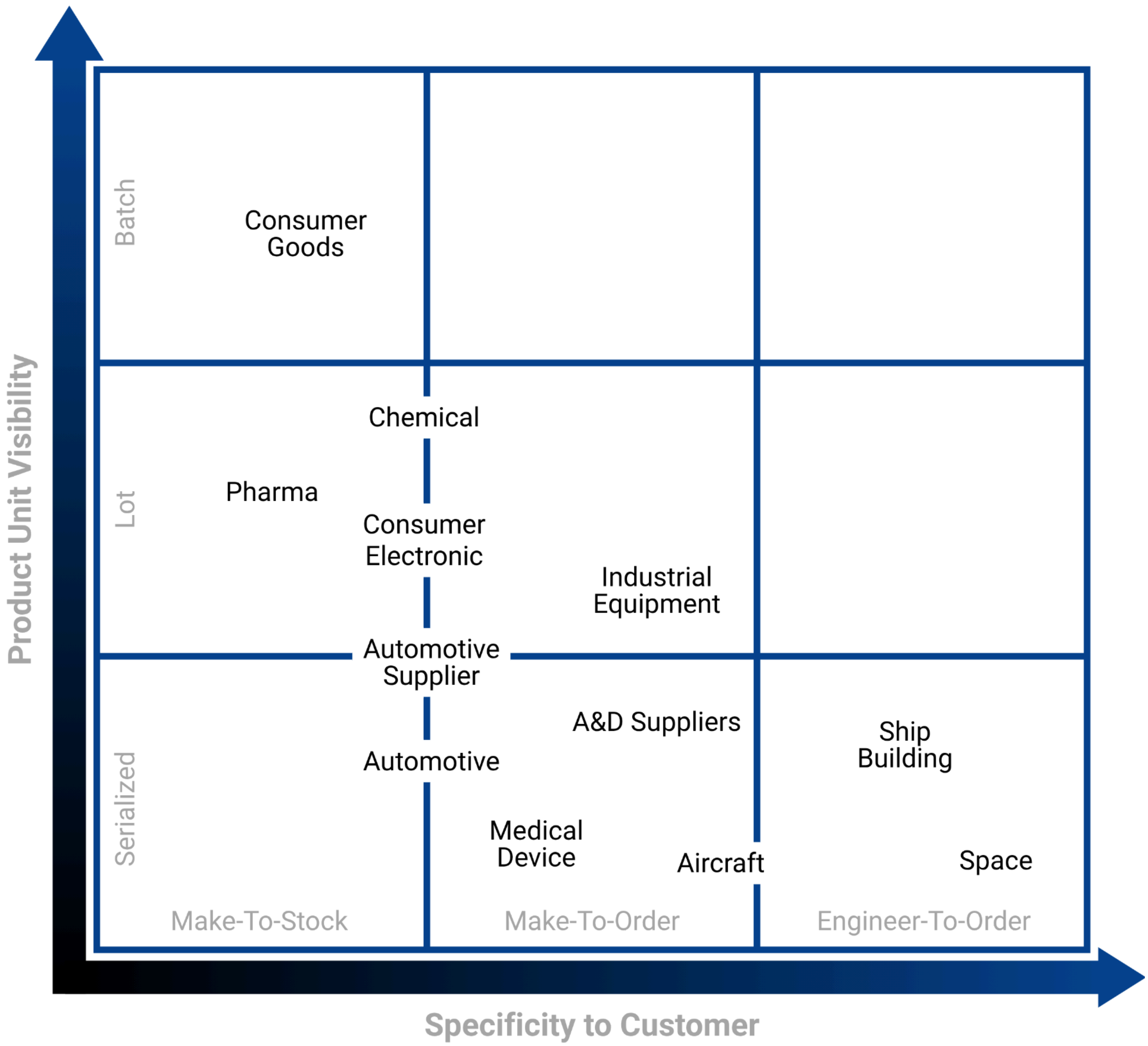
How work and workers flow for different types of manufacturing operations

Each type of manufacturing operation – whether it's a jet engine assembly line or a shipyard – structures and schedules work differently. As a result, how workers are deployed varies widely.



Observations in high-complexity, low-volume discrete manufacturing

Operation: Engine Assembly (Module & Final Assembly) in Aerospace
Specificity to Customer: Make-To-Order | Product Unit Visibility: Serialized
Rate (Example): Dozens of units per month per product model per shop

Observations on the work	
What is the process? Sources of operational complexity?	● A jet engine is made up of several major modules: Fan, Compressor, Combustion Chamber, Turbine, Nozzle ● Each module is assembled separately and then integrated ● Each engine may have custom specifications ● A shop may produce parts for both new make and aftermarket
How is the shop organized?	● Includes cells (station groups) and/or assembly lines ● Multiple sub-assembly lines may feed the main/final assembly line
How is work scheduled?	● Prioritization driven by serial numbers and respective delivery dates ● Often many jobs in various stages of progress from prior shift ● Supervisors have decision-making latitude to prioritize jobs each shift based on availability of parts, space, labor, inspectors, etc ● Shops juggle multiple products in various lifecycle stages and may be ramping to rate on one line/program while sunsetting another ● Inspections can be a production bottleneck. Given sequential dependency, mechanics often can't proceed to the next step until a quality inspector signs off.

Observations on the workers	
Are workers generalists or specialists?	● In assembly, mechanics may specialize in a specific module or work on the Critical Path given the sheer number of steps in each procedure. Procedures can take many hours and often carry-over from one shift to another.
How are workers scheduled?	● Assignments (i.e., who works on which parts) are typically determined by the Supervisor or Team Leader at the start of shift ● Assignments consider worker eligibility, efficiency (i.e., actual time vs standard time), and quality (i.e., history of defects) ● In module assembly, workers may focus on multiple instances of a specific module for an entire shift to reduce context switching ● In final assembly, workers follow a single engine (serial number) through all assembly stages, fostering ownership and continuity. They "walk to the work". ● Workers may be borrowed from different lines/shifts/overtime pool ● Certain tasks require multiple workers. Supervisors select workers with similar work pace and interpersonal compatibility ● Inspection demand-planning and inspector availability increasingly critical. Some mechanics are qualified to do low-risk inspections

Observations on machine-centric batch processing

Operation: Fabrication in Tooling/Industrial Equipment
Specificity to Customer: Make-To-Stock | Product Unit Visibility: Batch
Rate (Example): Highly variable; hundreds to low thousands of units per month per shop

Observations on the work	
What is the process? Sources of operational complexity?	● Can include a series of cutting, machining, grinding, milling, bending, welding, tumbling, and other shaping techniques ● Operational complexity is due to changeovers, which is the process of switching from the production of one product or part number to another in a machine by changing tools, dies, molds, fixtures, etc. It involves a variety of activities, including disassembling the previous setup, configuring the new one, staging materials, adjusting settings, and verifying the first good part.
How is the shop organized?	● Shops are typically organized in cells of machines/resources based on parts or families of parts produced
How is work scheduled?	● Parts are ordered by the customer in high volumes. Different parts might run through the same machines, so batching similar parts minimizes the need for changeover (e.g., machining smaller parts of similar type across multiple orders) ● Schedules are dictated by batches and progress on customer order ● Focus on optimizing machine utilization and minimizing downtime ● Production Schedulers may determine the long-term schedule and work with supervisors to decide the tactical details of assignment ● Many different types of job queuing / prioritization logic, including FIFO (first-in-first-out), SPT (shortest processing time), EDD (earliest due date), Setup-Time Minimization, etc.

Observations on the workers	
Are workers generalists or specialists?	● Different machines and processes and materials call for different skills. It also depends on whether processes are manual, semi-autoamated, or automated. ● The most skilled technicians are often those able to do setups, changeovers, and troubleshooting.
How are workers scheduled?	● Machine availability, state, and setup times are critical factors to headcount planning and job assignments ● Workers are typically assigned to specific machines or zones of machines and perform similar tasks to minimize changeovers ● Skilled machinists can run multiple machines at a time ● May find small teams made up technicians with different levels of skills (e.g., Level 1 + Level 2 + Process Tech); assigned as a team

Observations on highly-regulated process-oriented services

Operation: Maintenance, Repair, Overhaul (MRO) in Aerospace
Specificity to Customer: NA | Product Unit Visibility: Serialized
Rate (Example): Highly variable; hundreds to thousands of parts per month per shop

Observations on the work	
What is the process? Sources of operational complexity?	● Perform maintenance, repairs, and overhaul on aircraft components ● Routine checks can occur in the field or in designated maintenance bays (i.e., line maintenance), while heavier work (e.g., milestone structural checks/repairs, part replacements) occur at a service station (e.g., base maintenance). ● Major parts like engines and landing gear may be removed and shipped to a specialized repair center (shop-level maintenance). ● High complexity due to unpredictable maintenance needs and strict adherence to safety standards
How is the shop organized?	● For shop-level maintenance, plants are organized into “Gates” or cells for: ○ Disassembly ○ Inspect ○ Repair ○ Reassembly ○ Inspect ○ Test
How is work scheduled?	● Job scheduling is driven by aircraft service criticality, parts availability, space, and regulatory compliance

Observations on the workers	
Are workers generalists or specialists?	● Workers must have specific qualifications for specific tasks, which may be specific to a particular aircraft program or customer ● Workers often work on multiple products and programs ● Require objective evidence for regulator and customer audits
How are workers scheduled?	● Job assignments can change dynamically based on inspection outcomes and urgent repair needs

Observations on high-volume, continuous assembly lines

Operation: Final Car Assembly in Automotive
Specificity to Customer: Make-To-Stock | Product Unit Visibility: Serialized
Rate (Example): Tens of thousands of total units per month per plant

Observations on the work	
What is the process? Sources of operational complexity?	● Assemble vehicles in a sequential flow, emphasizing speed and consistent throughput. ● Cycle times often 5-15 minutes ● Increasing operational complexity due to mass personalization (e.g., each car has multiple trims, custom features, colors, etc.)
How is the shop organized?	● One assembly line may have 100+ stations and 100+ workers each, which are often broken down into zones of ~15-25 stations ● One line may run multiple products and models ● Large plants have multiple lines ● Note these lines are supported by large backshop teams (e.g., welding, fab, paint, upfit, etc.)
How is work scheduled?	● Prioritized by daily production targets by model type

Observations on the workers	
Are workers generalists or specialists?	● In assembly, most operators have a generalist set of skills, though they may lack experience (aka “touches”) with certain stations ● Many of these plants see high turnover and absenteeism, so there is a focus on workforce flexibility and versatility. For example, “3x3x3” is a concept where each worker is trained up to “level 3” (i.e., they can work without supervision) on 3 stations in 3 weeks from their hire date. This bench strength enables supervisors to move workers around more easily to fill short-term gaps.
How are workers scheduled?	● Some organizations/sites run robust rotation programs, which are intended to ensure full coverage of all stations required to run the line, while also trying to mitigate employee fatigue and injury. Different tasks have different ergonomic stress (e.g., heavy loads or repetitive motions), which we have seen included in the planning. This can be difficult to swiftly administer at scale. ● Cross-training across multiple stations provides versatility ● Critical stations are always staffed first ● New workers rotate through easier tasks until ready to advance. ● Real-time adjustments may be required to address absenteeism or production changes. ● Team leaders may cover if another worker is in training or on break

Observations on batch-based production with diverse SKUs

Operation: High-Mix Assembly in Electronics
Specificity to Customer: Make-To-Stock | Product Unit Visibility: Batch
Rate (Example): Tens of thousands of total units per month per plant

Observations on the work	
What is the process? Sources of operational complexity?	● Assemble a wide variety of electronic products, often in small batches (e.g., dozens or hundreds) ● Each batch corresponds to a production lot of identical units ● Combination of manual, semi-automated, or fully automated stations build products according to SKU-specific instructions ● Quality inspections at key checkpoints ● Operational complexity from product diversity and frequent changeovers ● There can be batch capacity & time-based interdependencies/ bottlenecks (e.g., rack capacities, oven capacities, etc.)
How is the shop organized?	● Typically linear or U-shaped flow within cells ● Support areas include kitting, rework, test stations
How is work scheduled?	● Driven by order completion percentages, equipment constraints, and batch priorities ● Dynamic production scheduling adjusts to changing priorities

Observations on the workers	
Are workers generalists or specialists?	● Generalists given SKU diversity and constant need to reallocate labor to where bottlenecks arise ● Process techs focus on programming, changeovers, troubleshooting
How are workers scheduled?	● Determine headcount based on batches days to weeks in advance ● Assignments consider skills, past performance, and quality records ● Workers may be re-tasked mid-shift as production bottlenecks shift (e.g., Test > Assembly).

Observations on large-scale, project-based construction

Operation: Shipbuilding
Specificity to Customer: Engineer-To-Order | Product Unit Visibility: Serialized
Rate (Example): 1-5 ships per year per shipyard

Observations on the work	
What is the process? Sources of operational complexity?	● Panels are assembled into larger modules or blocks. Each block may include internal outfitting (piping, cabling, HVAC) before being moved. Blocks are lifted and joined to form the hull in a dry dock or slipway. Major crane operations are tightly scheduled due to their criticality. Final systems installation: propulsion, electrical, navigation, HVAC, and accommodations. ● High complexity due to the scale of projects, the need for precise coordination, the confined physical spaces, customization ● Shipyards often juggling multiple programs and as a result ramping to rate on one/program while sunsetting another
How is the shop organized?	● The shipyard is organized by production stages that correspond to the ship's structure: fabrication, welding, assembly, erection, plus berths for final outfitting and testing
How is work scheduled?	● Long-range master production schedule (6-18 months lookahead) broken into medium (26 wks) and short-term planning (3-6 wks). ● Foremen, planners, and supervisors use these to identify potential blockers (missing materials, unresolved design issues), sequence tasks by zone and crew capability, confirm interdependencies (e.g., insulation must follow pipework), and review crew availability.

Observations on the workers	
Are workers generalists or specialists?	● Crews are organized by core trade disciplines, including steel workers, pipefitters, electricians, painters, HVAC technicians, outfitting teams (furniture, cables, insulation)
How are workers scheduled?	● Assignment begins by identifying which zones or blocks require which trade in the upcoming schedule window. ● A zone must be "open for work," meaning all predecessor tasks are complete, materials are available, physical access is safe ● Foremen, planners, and supervisors meet daily or weekly to review available workfronts (zones/blocks), review crew headcount and qualifications, coordinate handoffs between trades ● Supervisors consider crew skill mix, physical space limits, productivity history, fatigue rotation for safety in heavy-duty tasks ● Time and task completion is tracked per crew to evaluate productivity (e.g., man-hours per package) ● Underperforming crews may be reassigned, reinforced, or retrained

Additional considerations & complexities when choreographing work and workers (independent of manufacturing operation type)

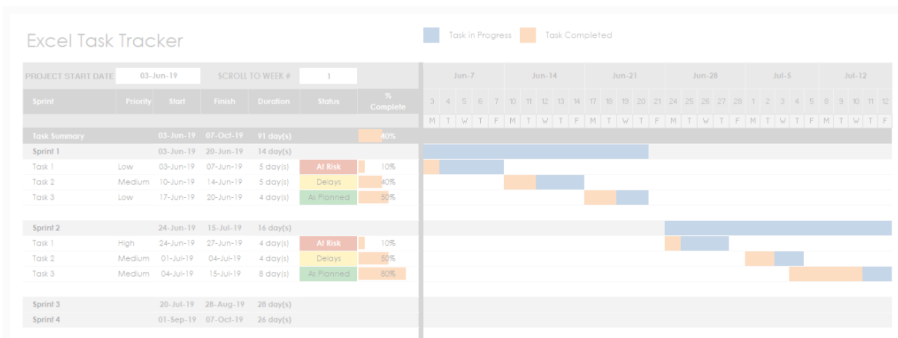
- Worker availability
  - Increase in variety of shift structures (5x8, 9x80, 4x10, etc.)
  - Increase in employers offering partial shifts, shift-swapping, and other flexibility
  - Planned vacations and PTO
  - Unexpected turnover or absenteeism
  - Overtime
- Adherence to union rules and regulations
  - Potential prioritization of assigning workers based on primary shift or seniority
  - Opportunity for workers to opt-in or out of overtime
  - Opportunity for workers to accept or decline new training

How flow of work and workers is determined today

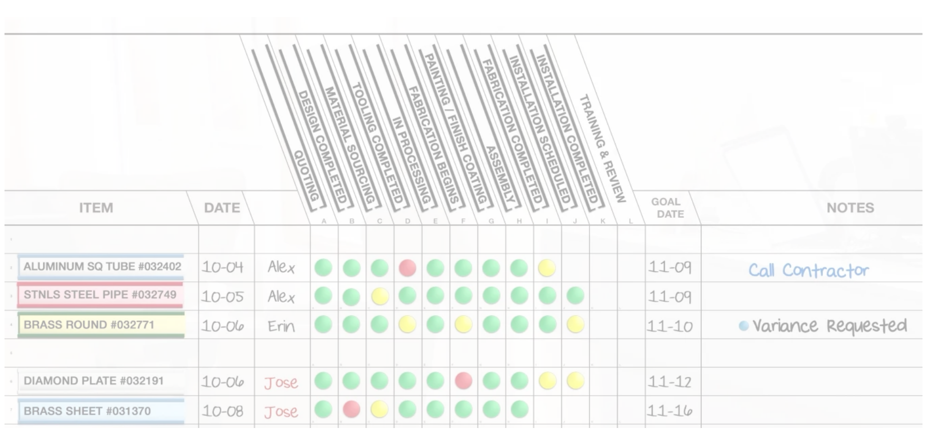
Work allocation decisions are generally done manually today following a four-step process.

Note that we are focusing on shift-level flow. This assumes that jobs for the week/month have been roughly scheduled based on work orders and that an assortment of trained/eligible workers are present.

- Step 1: Job Prioritization
    - Supervisors use paper forms and/or spreadsheets to track individual jobs and corresponding job progress shift-over-shift



- Step 2: Team management
    - Supervisors reconcile who is scheduled with who showed up that shift, plus their capabilities and work constraints
    - Understaffings elevated up to leadership to move resources around the floor
    - If a gap is identified in advance (days), supervisors reach out to the overtime list
- Step 3: Assignment Matchmaking
    - Default to what seemed to work yesterday and avoids personal confrontation
    - Handle exceptions
- Step 4: Communication
    - Print-outs and whiteboards, often with handwritten notes for last minute changes



Opportunities for more systematic and dynamic decision-making

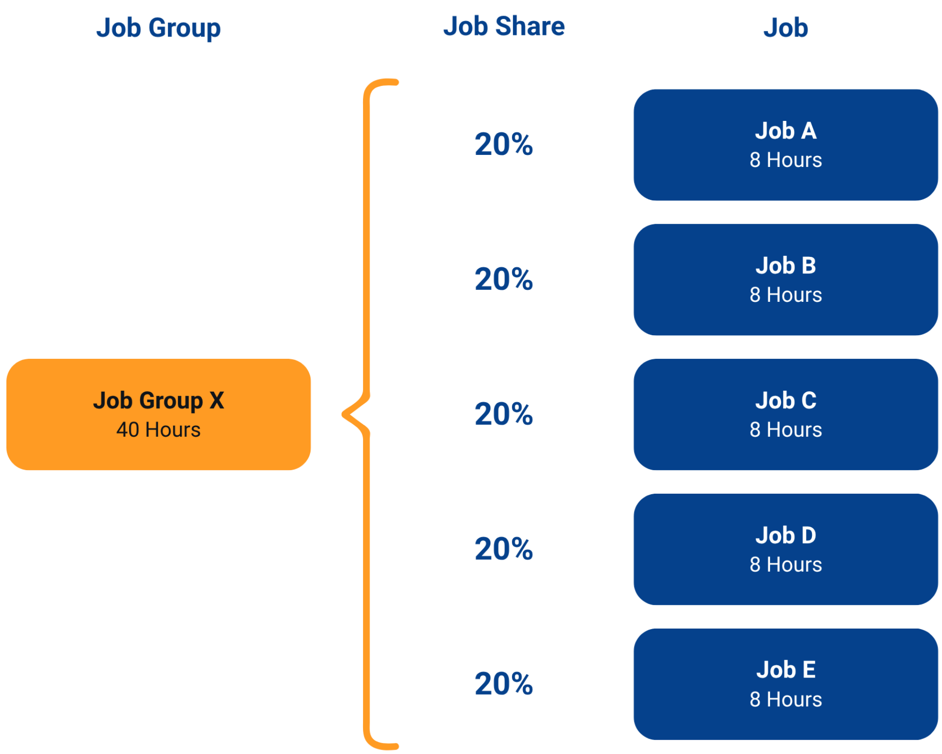
How productivity is calculated

First, if our goal is to demonstrate an increase in productivity, we must establish a methodology for calculating productivity.

Given the uniqueness of each type of manufacturing operation, we will pick one type for this initial analysis: high-complexity, low-volume discrete manufacturing (e.g., jet engine assembly).

Let's assume a **Job** is an assignable unit of work, and it takes a certain number of hours to complete. A sequence of **Jobs** makes up a **Job Group**, which represents a "Process" or "Routing". Each **Job** makes up a portion of the total hours of the **Job Group**. This is a metric we call **Job Share**.

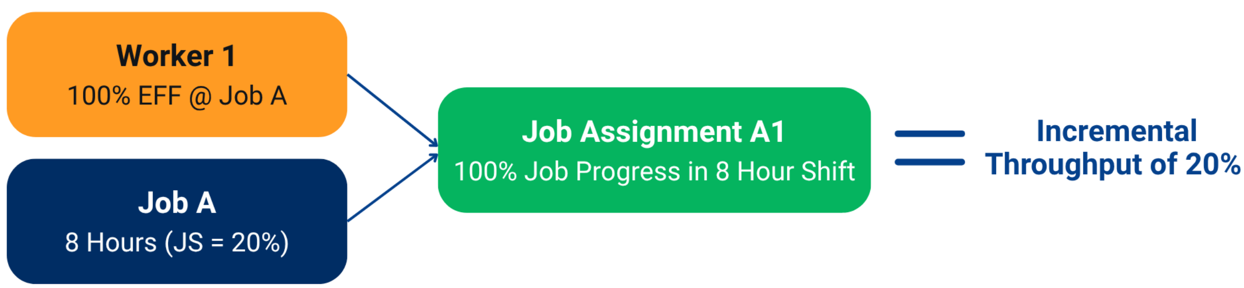
Job Share = Job Standard Time / Job Group Standard Time



Job Share can be a useful metric to calculate how much **Incremental Throughput** (progress) is made within a given time period.

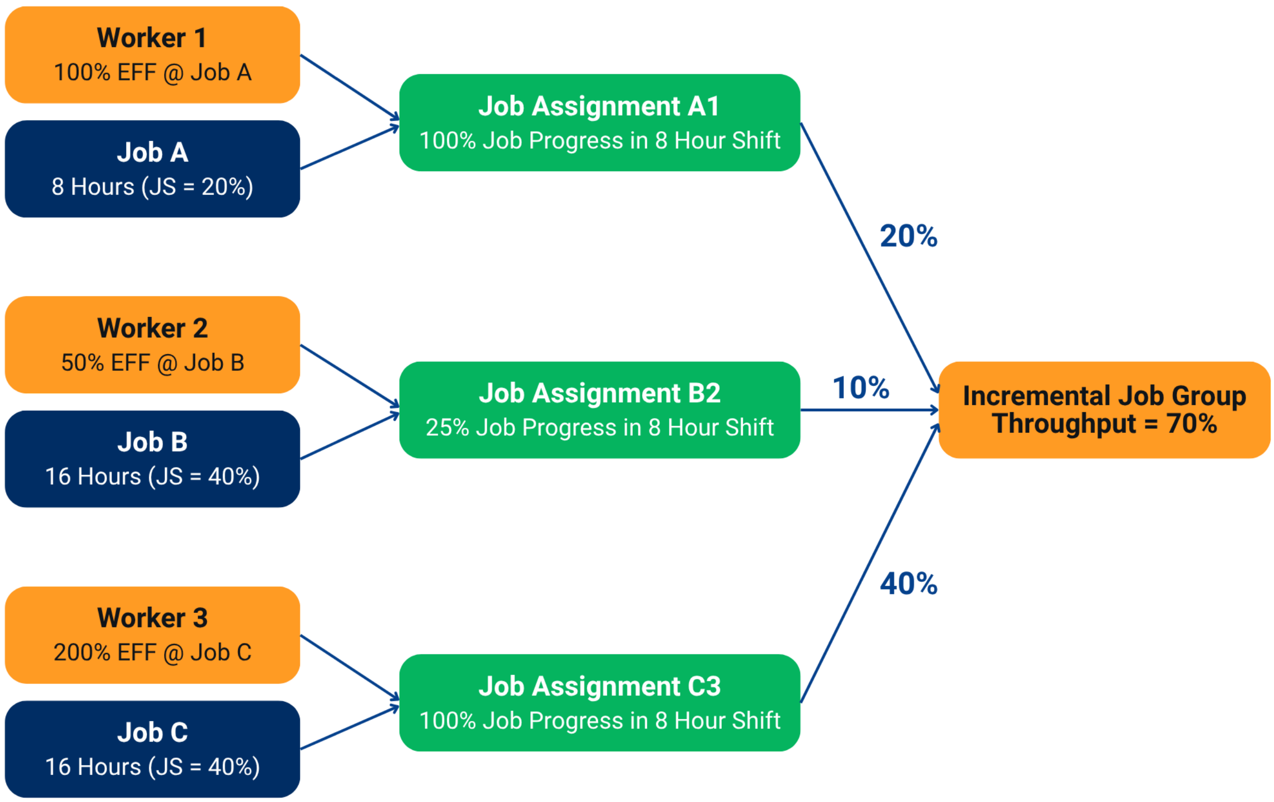
For example, let's assume a **Job** that takes 8 hours to complete has a **Job Share** of 20%. Now let's assign a worker that was 100% efficient, which means they will complete 100% of the **Job** within an 8 hour Shift (aka **Job Progress Completion %**). In this case, we would have 20% **Incremental Throughput** of the **Job Group**.

Incremental Throughput % = Job Share % * Job Progress Completion %



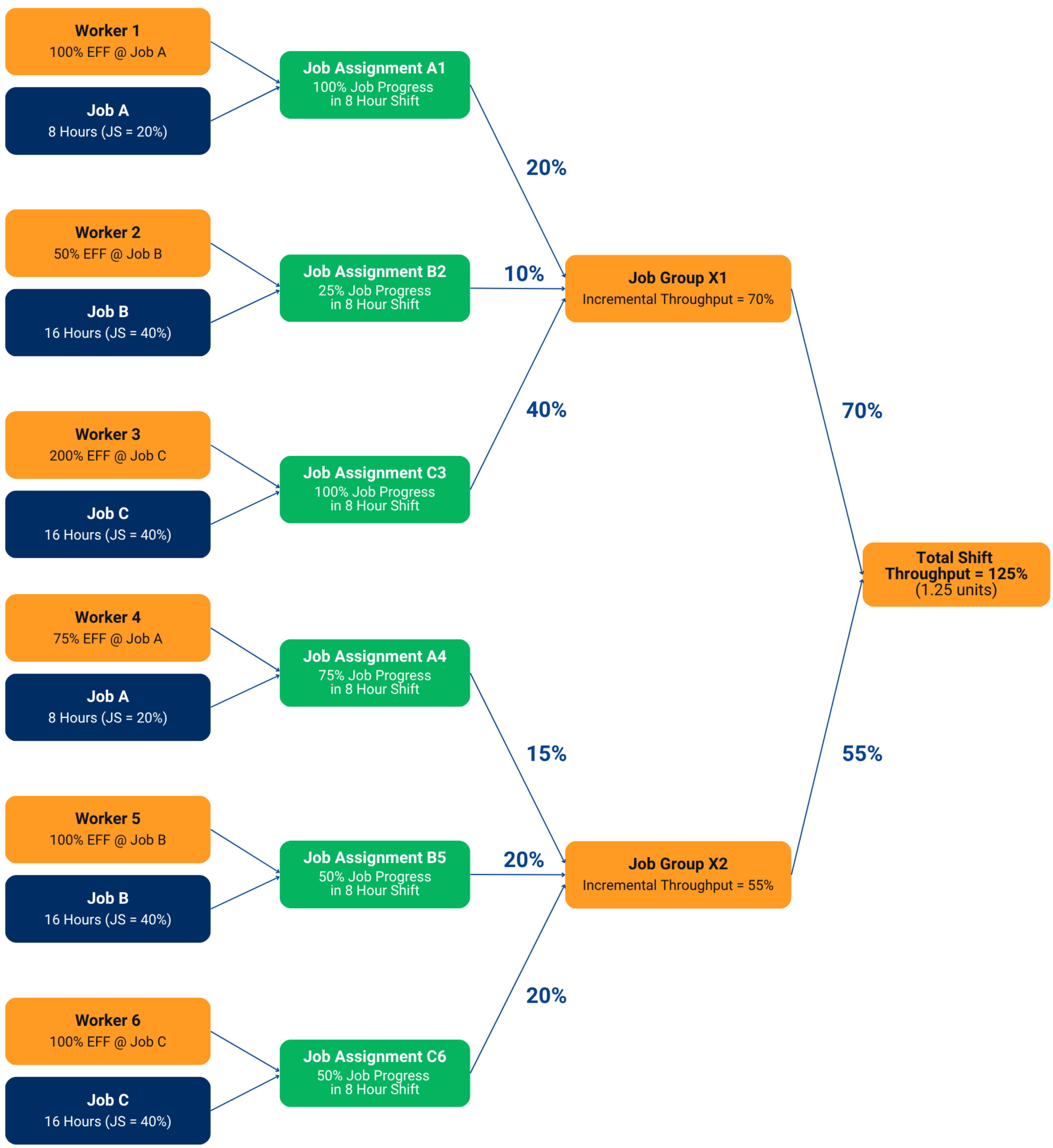
When looking at a collection of **Job Assignments**, summing the **Incremental Throughput** (progress) across each **Job Assignment** can determine the total **Incremental Throughput** made towards a **Job Group**.

Job Group Incremental Throughput = Sum of Incremental Throughput across Job Assignments



Similarly, if we sum **Incremental Throughput** for all **Job Groups** on a **Shift**, we get **Total Shift Throughput**.

Total Shift Throughput = Sum of Incremental Throughput across Job Groups

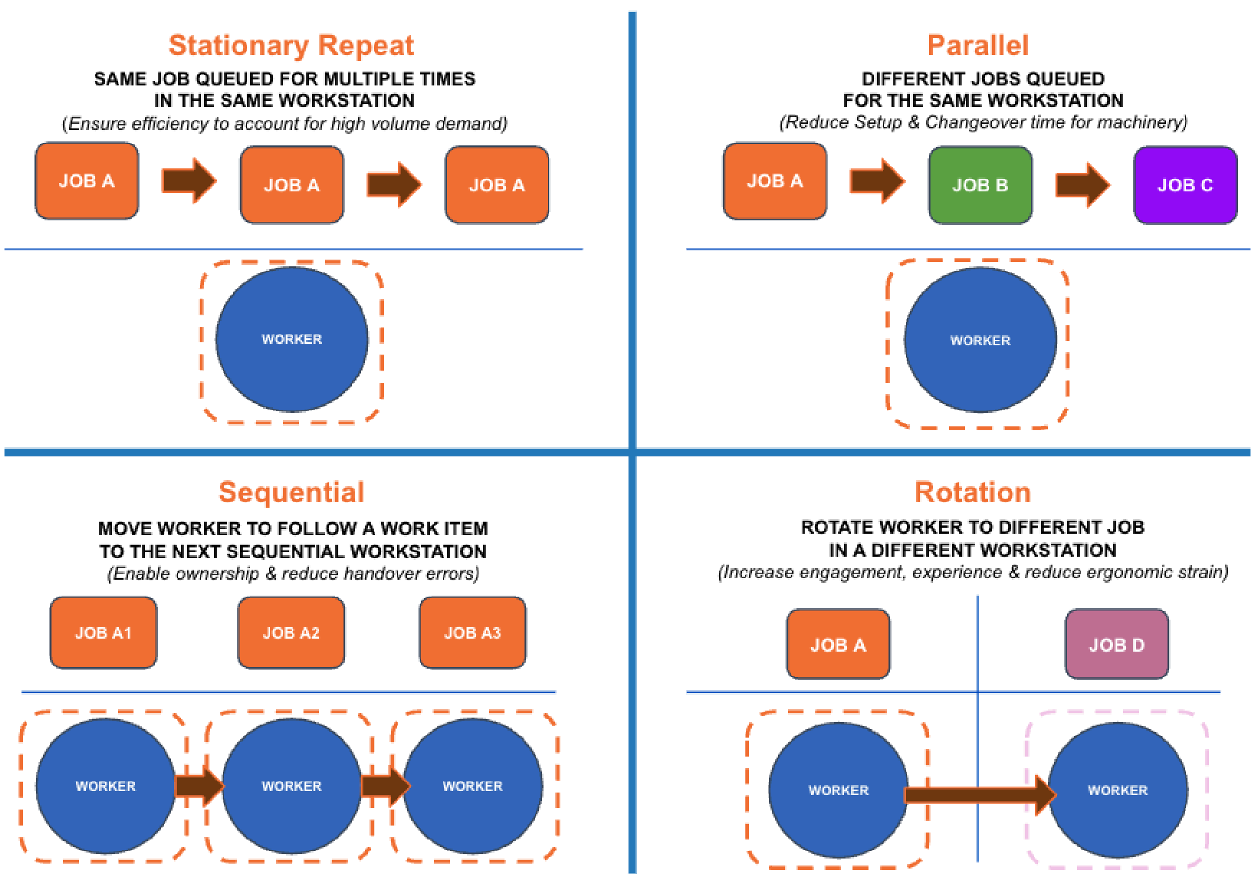


AI-based algorithms can account for many interdependent variables

Historically, the idea of centralizing and synthesizing all of the data that would be needed to systematically optimize the flow of work and workers was a daunting endeavor. However, advancements in and access to computing power and AI have made this more feasible today.

Based on our industry research, here is a breakdown of select variables that may need to be accounted for when optimizing the flow of work and workers, depending on the type of manufacturing operation.

Work-related variables can include:	Worker-related variables can include:
• Job Prioritization • Completion status from prior shift • Job Standard Time • Job queuing logic (detail below) • Job difficulty • Changeovers • Ergonomic load of each job	• Availability • Eligibility • Job history from Manufacturing Execution System (MES) including: ○ Job Count, Efficiency, Recency • Compatibility with co-workers for multi-headcount jobs



Statistical Analysis: Determining the Optimal Flow

We hypothesize that manufacturing operations can significantly improve productivity by algorithmically assigning work to workers.

This stems from the fact that the number of potential assignment configurations grows exponentially with the number of jobs and workers. For example, with no constraints, there are 3.6 million ways to assign 10 workers to 10 jobs. This scale makes it infeasible for even the most experienced supervisors to manually determine the optimal configuration for a metric like Throughput.

Today, most production schedulers and frontline leaders lack the tools to quantify the cost of suboptimal assignments. As a result, inefficiencies often go unnoticed or are written off as acceptable variance rather than opportunities for improvement.

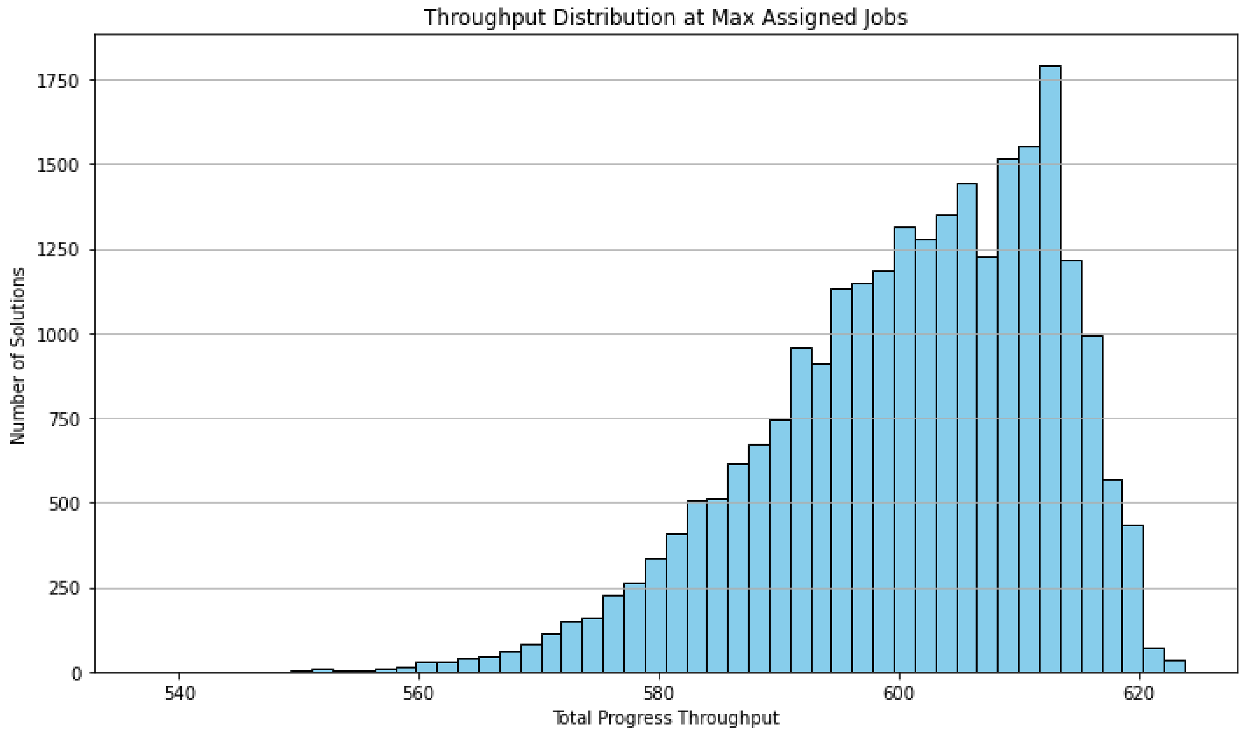
To test our hypothesis, we conducted a statistical analysis on a complex jet engine module assembly line with 16 available workers and 25 jobs on one shift.

Even in this tightly scoped scenario, the model produced 78,000 possible assignment configurations when accounting for key operational constraints:

- **Job Dependencies** – Sequencing constraints (e.g., a module can only begin after a sub-module is complete)
- **Headcount Requirements** – The number of workers required per job
- **Standard Time** – Time needed per job relative to shift capacity
- **Worker Eligibility** – Whether a worker is qualified to perform a given job

We then added a constraint that each worker must be assigned at least one job at the start of the shift – thereby maximizing the utilization of the available workforce. The number of valid configurations still totaled ~25,000.

Importantly, the ~25,000 configurations produced a wide range of outcomes in terms of Total Throughput. We observed 4,825 unique Throughput values, ranging from 5.37 to 6.23 work orders completed in a single shift – a ~15% difference between the least and most productive schedules. Extrapolated across a month, this could translate to roughly one additional engine every seven shifts, or roughly six incremental engines per month.



To explain why this distribution is happening, think of a worker as a scarce resource. Assigning the most efficient worker to one job prevents them from being assigned another job running at the same time. And job-specific efficiency matters. McKinsey research shows that: “Productivity gaps between high and low performers increase by as much as 800 percent as a task increases in complexity. Even manufacturers operating in the lowest-complexity jobs still experience a 50 percent premium between high and low performers.”[1]

Now consider how different jobs may be in different stages of completion from the prior shift, may have different Standard Times, or may have one or many eligible workers available. There are many variables at play, and each job assignment impacts the availability of that worker for subsequent job assignments on that same shift.

While many assignment configurations yield full worker utilization and appear “fully loaded”, the actual throughput can differ significantly depending on which jobs are assigned in what order and to who.

We cannot assume a supervisor is consistently selecting the lowest-performing configuration, but we also cannot assume that a supervisor is consistently selecting the highest-performing configuration during pre-shift planning.

Determining the optimal flow algorithmically ensures maximum throughput given available resources, and it does so without adding any incremental headcount.

[1] Scott Keller and Mary Meaney, “Attracting and retaining the right talent,” McKinsey, November 24, 2017.

Review of technology already in market based on publicly-available information

As part of our research, our team discovered two robust software applications purpose-built to deliver similar value. Both applications were designed and developed in-house by large automotive OEMs to optimize staffing on their continuous assembly lines. These applications are not available commercially off-the-shelf, but there is some publicly available information on each:

- Volkswagen’s Daily Assignment Rotation Tool (DART)
  - Digital system that systematically manages shop-floor job rotations.
  - The tool schedules production operators to switch tasks every 2 hours to avoid fatigue and repetitive strain. It accounts for each workers’ qualifications and attendance.
  - DART integrates with VW’s Digital Production Platform and factory data, providing a real-time view of who is working at each station.

- Toyota’s Team Member Rotation Application (TMRA)
  - The tool maintains each worker’s certified skills.
  - It automatically generates rotation plans at the start of each shift that ensure everyone moves through a variety of tasks every 2 hours.
  - It classifies jobs by ergonomic intensity (green, yellow, or red based on physical strain) and sequences rotations to prevent anyone from staying on a high-strain “red” job too long.

Implications & Conclusion

- Productivity improvement
    - For certain types of manufacturing operations, there are material gains to be realized. Our statistical analysis of a complex engine assembly operation showed ~15% gains in Throughput. Note that this does not necessarily apply apples-to-apples to continuous assembly or other types of operations.
    - The statistical analysis could also be packaged in a way to compare different production scenarios to understand the impact of different “batting orders”.
- Supervisor effectiveness
    - Supervisors may spend 20-30 minutes pre-shift doing the mental gymnastics needed to determine assignments or rotations. A technology solution has been shown to give at least 30% of that time back.
    - We also often hear it takes weeks to months on the job for a supervisor to get a full sense of what the work consists of and what each worker is capable of. This type of modeling makes the decision-making ability of a supervisor that is new to the line/department as effective as an experienced supervisor on Day 1.
    - A technology solution may also be able to systematically look across zones and lines to utilize all available resources on site.
- Workforce training
    - Cross-training is often prohibitively expensive because it’s difficult to justify taking trainers and trainees (and potentially machines and materials) out of production. It’s one of the reasons we often see the most capable workers turn into a small, flexible team of floaters to address overflow and exceptions. However, our findings suggest that:
        - Cross-training plans can be strategically prioritized using Total Projected Throughout. As an example, imagine an auto-generated recommendation to a supervisor or training team member that suggests they could increase Total Projected Throughput (i.e., unlock a new assignment configuration) if certain workers were cross-trained on certain jobs.
        - Imagine if a supervisor were able to assign the recommended training to workers during idle windows in the shift schedule (e.g., shadow X worker on Y job) and visually display the training block on the shift schedule.
- Other variables that could be incorporated into the algorithm
    - New hire ramp plan
        - Automatically assign easier jobs until new hires demonstrate proficiency
    - Training refreshers and renewals
        - Automatically get touches on Jobs to prevent skill decay and/or expiration
    - Elevate opportunities for high-value cross-training
        - In the event workers go unassigned during a shift, they can be assigned training that strategically increases bench strength

There is an opportunity for manufacturers to drive step-change gains in productivity by processing this complexity in real time.

About Covalent

Covalent was launched out of a research initiative at Harvard in 2017. Today, Covalent is the global leader in Workforce Operations solutions for complex discrete manufacturers. The company enables hundreds of critical factories and repair shops to systematically administer and optimize workforce planning, development, and deployment for tens of thousands of workers worldwide – empowering Manufacturing and Quality leaders to make credible decisions that improve production performance. We're proud to serve 3 of the top 5 aerospace & defense manufacturers, as well as Mercury Marine, Polaris, MasterCraft, and Great Dane. To learn more, visit www.covalent.works