Verification of Production Capacity Estimates: Routing Data, Parallel Resources, and Bottleneck Identification

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Abstract

Production capacity estimates depend on the relationship between product routes, resource availability, and the selected product mix. This paper develops a verification method for deterministic workload-based capacity bounds and demonstrates it with a synthetic two-product, two-resource system. For a fixed equal mix, one resource has two parallel machines and the other has one; each machine supplies 420 available minutes. Correct routing gives a nominal bound of 140 units per period. Omitting one product operation increases the reported bound to 210 units, while duplicating the bottleneck workload reduces it to 70. Duplicating only the nonbottleneck workload leaves the overall bound unchanged but creates a false bottleneck tie. Additional calculations examine setup allowances and a specified rework-visit assumption. Numerical checks establish the results and distinguish nominal load feasibility from achievable throughput. No shop-floor measurements, scheduling benchmark, or realized capacity increase is claimed. The contribution is an auditable verification case for engineering planning information systems.

Keywords: production capacity; routing verification; parallel resources; bottleneck analysis; workload; manufacturing planning.

1. Introduction

Capacity planning connects demand, routes, resource calendars, and operational assumptions. Indicators used in production management are interdependent [1, 2], so a wrong route or calendar can affect several reports at once. A plausible capacity total may still misidentify the resource that constrains production.

This study examines a deterministic load model before considering detailed scheduling or stochastic flow. Bottleneck methods address several different operational meanings [3]. The limiting resource in the present model is specifically the resource with the smallest workload-based capacity bound for the declared fixed mix.

The study examines both scalar capacity and the explanation attached to it. A planning system may correctly report a total while naming the wrong limiting resource because two workload errors or constraints happen to coincide. Such a report can still misdirect an equipment purchase or process-improvement effort. The paper therefore retains product-resource contributions and tests each resource bound separately, allowing the reader to distinguish agreement in the final minimum from correctness of the underlying planning model.

2. Capacity model

2.1 Resource workload

Let p_j be the fraction of product j in a fixed mix, with fractions summing to one. Let t_jr be the processing minutes required at resource r per unit of product j, including explicitly modeled repeat visits. Average resource work per finished unit is w_r = sum(p_j t_jr). If resource r supplies H_r machine-minutes per period, its nominal unit bound is C_r = H_r/w_r for positive w_r.

The system bound is C = min_r C_r. This is a necessary workload condition under the stated pooling assumptions, not a guarantee that a feasible schedule or stable throughput of C exists. Sequence constraints, setups, labor sharing, blocking, and variability can make achievable output lower.

2.2 Parallel capacity and calendars

For m identical machines with h available minutes each, H = m h only if the machines are genuinely available to the same workload and no omitted shared constraint prevents simultaneous use. Distinct machine capabilities require separate eligibility constraints. Treating every machine with the same department label as interchangeable can overstate capacity.

The model uses processing time in minutes per unit and calendar availability in machine-minutes [4]. Resource calendar intervals require consistent timestamp interpretation [5]. Planned breaks are already excluded from the 420-minute availability in the fixture. A utilization or OEE adjustment should not be applied again without checking whether the same losses were already removed.

Equipment-effectiveness literature provides context for availability and performance reporting [6, 7]. However, substituting a historical effectiveness percentage into a capacity model changes its assumptions. The report should identify whether times and calendars represent ideal, standard, observed, or derated operation.

A resource requirement may consist of simultaneous demands on a machine and an operator. Adding machine minutes alone cannot represent that coupled constraint. Similarly, alternative routes require a choice of routing fractions rather than summing every alternative as if all operations were mandatory. The present fixture has one mandatory route per product and no shared labor limitation. These restrictions make the calculations transparent while identifying exactly which additional constraints must be introduced before applying the method to a more complex shop.

3. Synthetic routing and reference bound

3.1 Fixed product mix

Product A requires 2 minutes at R1 and 4 minutes at R2. Product B requires 4 minutes at R1 and 2 minutes at R2. The selected mix is 50% A and 50% B. R1 has two parallel machines and R2 has one, each with 420 available minutes. Average workload is 3 minutes per finished unit at both resources.

Table 1. Synthetic routing and resource data.

Product or resource	R1	R2
Product A processing time	2 min/unit	4 min/unit
Product B processing time	4 min/unit	2 min/unit
Available parallel machines	2	1
Total available machine-minutes	840	420

The nominal bounds are 280 units at R1 and 140 at R2, giving system bound 140. At a plan of 60 units of each product, both resources require 360 machine-minutes. Utilization is 42.8571% at R1 and 85.7143% at R2. These fractions are workload ratios, not measured busy-time fractions from a factory.

3.2 Identity of route operations

Each route operation should be identified by product revision, operation instance, and resource requirement. A repeated visit to the same resource can be legitimate. Deduplicating only by product and resource would incorrectly remove that visit. Conversely, an operation joined to multiple tool or qualification records must not be counted repeatedly.

Data cleaning must preserve business identity rather than remove equal numeric values indiscriminately [8]. Fitness for the planning question includes the completeness and applicability of the route [9]. A syntactically valid route table can still omit a required operation or assign it to an unavailable resource.

The data model should retain operation sequence even though the simple workload sum does not use it. Sequence becomes necessary when assessing whether the nominal bound can be scheduled and whether intermediate storage or transport is feasible. A verified aggregate workload is therefore an intermediate artifact, not a replacement for the route itself. Removing sequence information during reporting can make a later scheduling validation impossible even when the original data contained the required evidence.

4. Routing mutations and bottleneck effects

4.1 Isolated errors

If B's operation at R2 is omitted, average R2 work falls from 3 to 2 minutes per unit. The reported system bound becomes min(280,210) = 210 units. If all R2 workload is duplicated, average work becomes 6 minutes and the bound falls to 70. Neither mutation changes the actual stipulated manufacturing route.

Duplicating only R1 workload changes its bound from 280 to 140, leaving the system bound at 140 but creating a tie with R2. This cancellation at the system level can misdirect an improvement analysis even though the total capacity appears correct. Each resource's load and capacity must therefore be verified independently.

Table 2. Computed capacity-bound variants for the fixed mix.

Variant	R1 bound	R2 bound	System bound
Reference routes	280	140	140
B operation at R2 omitted	280	210	210
R2 workload duplicated	280	70	70
R1 workload duplicated	140	140	140

4.2 Product-mix sensitivity

The capacity bound is conditional on the 50:50 mix. Producing only A gives resource bounds 420 and 105 units; producing only B gives 210 and 210. These are different planning questions. Comparing their totals as though they were changes in equipment performance would confuse demand composition with physical improvement.

For arbitrary mix fraction p of A, workloads are w_R1 = 4 - 2p and w_R2 = 2 + 2p. The resulting capacity curve can be derived directly from the two resource bounds. Any reported capacity should therefore retain the mix assumption rather than present one scalar as an unconditional property of the factory.

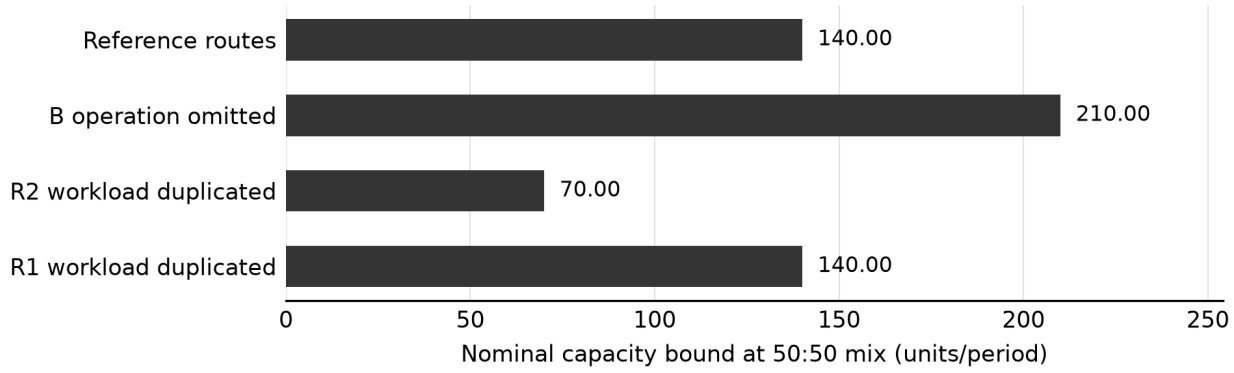


Figure 1. Routing faults alter a fixed-mix capacity bound; duplicating R1 workload leaves the total unchanged but creates a false bottleneck tie.

5. Setups, rework, and flow limitations

5.1 Explicit adjustments

If 40 R2 minutes are reserved for setup in the reference period, its processing availability becomes 380 minutes and the bound becomes 126.6667 units. The subtraction is valid here because the scenario stipulates a fixed setup allowance independent of sequence and batch size. A sequence-dependent setup model would require additional scheduling information.

If each unit independently requires one additional full R2 visit with probability 0.10 and no further rework, expected R2 work becomes 3.3 minutes per unit, giving 127.2727 units. This is an expected-workload bound, not a guarantee for an individual period. If rework can repeat geometrically, the expected visit multiplier is instead 1/(1-0.10), yielding a different bound. The repeat-visit model must be stated.

5.2 Throughput and queueing

Queueing models describe interactions and variability that a deterministic workload calculation omits [10]. A nominal utilization below one is not sufficient to guarantee acceptable lead time. For illustration, the factor u/(1-u) rises from 4 at u = 0.8 to 9 at u = 0.9. This arithmetic illustrates sensitivity near full utilization; it is not a calibrated waiting-time prediction.

Little's relation L = lambda W supplies a separate consistency check for compatible long-run averages [11]. For an assumed throughput of 20 units per hour and mean flow time of 3 hours, average work in process is 60 units. The relation does not identify which resource is the bottleneck or prove a schedule feasible.

Operational bottleneck methods can use behavior such as active periods [12], whereas the present bottleneck is defined by resource workload. These definitions should not be interchanged without analysis. A resource can appear limiting in the nominal model but experience starvation or blocking under actual line dynamics.

Calendar adjustments can also be counted twice. If the 420 available minutes already exclude a planned setup allowance, subtracting the same 40 minutes again understates the nominal bound. If historical processing times already include expected minor stops, multiplying by an additional performance factor may repeat that derating. The verification record should identify the losses included in each input rather than rely on names such as standard time or effective capacity, which can have different meanings across systems.

6. Verification procedure

6.1 Structural checks

The proposed procedure validates route completeness, operation identity, product revision, resource eligibility, processing-time units, and calendar scope. It then calculates product-resource contributions before aggregation. The resulting load matrix is retained so that a planner can inspect why a resource appears limiting.

Data-quality assessment should record missing operations, unmatched revisions, and unavailable resource assignments [13]. Remediation should address the responsible planning or master-data process [14]. Replacing a missing processing time with zero merely to complete a report turns incomplete evidence into an optimistic capacity claim.

Table 3. Verification rules for routing-based capacity estimates.

Verification rule	Expected result	Fault exposed
Split one operation into equivalent steps	Workload unchanged	Incorrect operation aggregation
Join a descriptive resource attribute	Workload unchanged	One-to-many fan-out
Add an eligible parallel machine	Resource minutes increase explicitly	Calendar or eligibility mismatch
Change product mix	Capacity recomputed and labeled	Hidden mix assumption

6.2 Workload checks and acceptance

At the reference demand of 60 units of each product, R1 requires 60(2) + 60(4) = 360 minutes and R2 requires 60(4) + 60(2) = 360 minutes. Splitting A's two-minute R1 operation into two one-minute steps preserves its per-unit workload and both resource totals. Such predictable transformations are examples of metamorphic testing [15]. The small route matrix is independently hand-calculable, providing a direct expected-answer oracle [16].

An implementation should also test missing routes, zero-demand products, unavailable machines, and legitimate repeated visits. These extensions are proposed coverage targets, not measured results of a large test suite. The demonstrated checks are limited to the numerical cases and invariance relationships stated here.

Verification of the load calculation is distinct from validation of a production model [17]. Any claim about achievable throughput would require further evidence, such as a validated schedule, a simulation with justified distributions, or an appropriate field study.

A capacity test should distinguish a new independent resource from a second record describing an existing machine. Only the former adds physical machine-minutes. An equipment table joined to two maintenance categories should not double available capacity any more than a route joined to two tools should double workload. Because numerator and denominator fan-out can cancel, checking only utilization can miss both faults. Independent resource counts and operation contributions are needed to verify the ratio.

7. Engineering use and automated reporting

7.1 Decision record

A capacity report should state the product mix, demand scale, resource calendars, applicable route revisions, setup treatment, repeat-visit assumptions, and the calculated bound for each resource. A recommendation to add capacity should also identify which constraints were omitted. Otherwise, a correct load calculation can be overinterpreted as a complete investment analysis.

Measurement and estimation uncertainty in processing times can affect the bound. The GUM provides general principles for uncertainty models [18], but a minimum of several uncertain resource capacities can have behavior that a simple symmetric error bar does not describe. Scenario analysis should show how plausible time and calendar changes alter the limiting resource.

Provenance records can connect each workload contribution to its route and calendar source [19]. Historical comparisons should preserve the versions used at the time of planning. A corrected route can change the reported bottleneck without any physical alteration of the line.

7.2 Automated database queries

ReToolSQL investigates verification and repair of generated SQL using execution feedback [20]. A relevant application would retrieve and check the route and resource records supporting a capacity calculation. The execution result does not determine whether two machines are interchangeable or whether setup time has already been deducted.

Candidate queries should be tested for duplicated operation contributions and omitted resource requirements. An automated repair must preserve legitimate repeat visits. When the demand mix is missing, the system should request or clearly parameterize it rather than silently assume the historic mix.

The proposed interface should describe its output as a workload-based capacity bound. It should avoid promising a feasible production schedule unless a scheduling analysis has actually been performed. This distinction makes the result useful without overstating the evidence supplied by the calculation.

When selecting an improvement, the report can show the effect of changing one constraint while holding the mix and other assumptions fixed. Adding R1 capacity in the reference fixture does not raise the nominal system bound because R2 remains limiting. Adding R2 capacity can shift the limiting resource to R1. This is an inference within the load model, not an investment recommendation. Physical feasibility, costs, staffing, and variability would still need evaluation before selecting an intervention.

8. Discussion and conclusions

8.1 Main findings

The synthetic results show that route errors can change the nominal capacity bound by large amounts and can also leave the total unchanged while corrupting bottleneck identification. The latter case is particularly important for improvement planning: agreement in the final scalar does not verify the resource-level explanation.

The fixed-mix model intentionally excludes sequence-dependent setup, shared labor, finite buffers, transport, and stochastic failures. Its result is a transparent necessary workload condition under declared assumptions. It should be used as a screening and reconciliation tool rather than a complete forecast of production output.

8.2 Industrial evaluation

A subsequent study should independently trace selected product routes, verify processing-time applicability, and reconcile resource calendars with actual eligibility. It should compare resource loads and bottleneck rankings before comparing total capacity. Review should include legitimate alternative routes and repeated operations to detect overaggressive deduplication.

An operational validation could then compare the corrected workload model with schedules or measured production under known mix and conditions. Differences caused by variability, blocking, and setup should be reported separately from database faults. A successful master-data correction is not automatically evidence that physical production capacity increased.

The framework also makes model revisions auditable. Changing the product mix, adding a legitimate repeat operation, and correcting a duplicated row can all alter a capacity estimate, but they represent different events. A useful historical comparison attributes the change to those causes rather than labeling every increase as improvement or every decrease as deterioration. That distinction helps planners explain why a verified forecast changed while preserving confidence in the underlying production records.

8.3 Conclusion

Capacity-estimate verification requires preserving operation identity, product-mix assumptions, and resource availability. Resource-level reconciliation is necessary because a correct system bound can conceal an incorrect bottleneck explanation. Explicit setup and rework assumptions prevent expected workload from being mistaken for guaranteed output.

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