Research Square

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Carbon Break Even Conditions for Cooling Selection in Precision Turning

Chukwuyem David Ukala
: University of Nottingham Faculty of Engineering
Eunice Iyaduni Ogunrotimi
University of Benin
Chijioke C. Chuwa
Northumbria University - City Campus: Northumbria University
Olanrewaju O Oladapo
University of Ibadan
Daniel O. Olokpo
FRANCIS TOBI OMIGBODUN
omigboduntobi@gmail.com

New Model Institute for Technology and Engineering
Lukman O. Kolawole
Middlesex University - Enfield Campus: Middlesex University

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Abstract

Minimum quantity lubrication can reduce fluid consumption while increasing compressed air demand, making its carbon advantage dependent on machining quality and tooling performance. This study develops an analytical method for selecting cooling strategies using emissions per accepted turned component. The method combines machine electricity, compressed air, net fluid consumption, cutting edge service and rejected workpieces within a consistent product boundary. Closed form expressions establish the minimum acceptable yield, maximum air demand and minimum cutting edge capacity required for minimum quantity lubrication to outperform flood cooling. An explicitly assumed steel turning case demonstrates the calculations without claiming experimental validation. At the selected electricity factor, minimum quantity lubrication reduces carbon intensity from 4.7177 to 4.6949 kg carbon dioxide equivalent per accepted component, a conditional improvement of 0.48%. Increasing rejection from 2% to 3% reverses that ranking. The corresponding air threshold is 1.558 cubic metres per attempted component. Joint interval analysis also identifies conditions under which neither strategy dominates. The contribution is a reproducible decision method that connects cooling selection to measurable production limits and identifies the evidence required for industrial verification.

1 Introduction

Cooling selection in precision turning affects more than the electricity consumed during a cutting pass. A change in lubrication can alter cutting forces, surface finish, tool replacement frequency, fluid losses and the number of components that satisfy the drawing. Manufacturing engineers therefore need to know whether a proposed cooling change reduces emissions for the required production output. A comparison based only on spindle power or lubricant flow can answer a different question. The relevant outcome is the carbon burden of an accepted component produced to an equivalent specification, with the consequences of unsuccessful machining included.

Research on manufacturing energy has established why the machine boundary matters. Kara and Li developed an empirical relationship between specific energy and material removal, and Li and Kara examined the total electricity required for turning [1], [2]. Component models and machine-efficiency research show that auxiliaries and non-cutting states can materially influence total consumption [3], [4]. Consequently, a lubrication strategy that decreases cutting force does not necessarily decrease machine electricity by the same proportion. Pumping, compressed air, extraction and waiting time must be assigned to the production activity that requires them.

Minimum quantity lubrication, abbreviated MQL, is attractive because it delivers a small lubricant supply close to the cutting interface. Experimental turning studies have examined its effects on temperature, wear and surface finish for specific material and tool combinations [5], [6]. These studies establish credible mechanisms and practical opportunities. They do not establish an unconditional environmental ranking across steels, superalloys, machine configurations and component specifications. Carbon

comparisons must retain the conditions under which the cutting results were obtained. A longer tool life measured at one speed cannot be transferred directly to a different production route.

Environmental assessments reinforce this need for a wider inventory. Campitelli and colleagues identified electricity, compressed air and lubricant provision as relevant contributors when comparing conventional lubrication with MQL [7]. Cutting-fluid strategies also involve cleaning, maintenance and treatment choices [8], [9]. These contributions can move in opposing directions. Reducing circulating liquid may increase pneumatic demand, while lower wear may reduce the manufacturing burden allocated from carbide tools. Life-cycle studies of cemented carbide and machining tooling support including these upstream contributions rather than treating a cutting edge as an emissions-free accessory [10], [11].

A second difficulty concerns the distinction between a product footprint and an organisation's emissions inventory. Product carbon accounting follows the processes required to provide a defined output [12], [13]. Corporate Scope 3 accounting instead classifies indirect value-chain emissions relative to the reporting organisation [14]. Electricity purchased for a manufacturer's compressor does not become that manufacturer's Scope 3 emission merely because the air supports machining. The distinction matters when electricity, purchased tools and supplier footprints are assembled from different records. Adding overlapping accounts can produce a precise-looking result with an incorrect boundary.

The trade-off is visible in published cutting experiments. Khanna and colleagues found that an environmentally favourable MQL strategy for titanium could also have poorer tool life and surface quality [15]. Contemporary sustainable-machining research accordingly treats resource use, tooling and process performance as connected outcomes [16]. That evidence motivates a conditional decision rule rather than a universal preference.

This paper addresses the decision that remains after an eligible manufacturing route has been identified: under what combination of accepted yield, compressed air demand and usable cutting-edge capacity does MQL have a smaller carbon burden than flood cooling? Earlier machining assessments provide the physical and environmental basis for this question. The present contribution integrates these quantities into explicit switching conditions and separates consumed tool service from the temporary opening of additional edges. The resulting thresholds can be checked directly against production records, without requiring an uncalibrated wear law or a digital-twin implementation. It also expresses continuous analytical limits as attainable whole-component and whole-edge decisions.

The study develops closed form inequalities, applies them to a fully disclosed steel-turning example and examines simultaneous parameter bounds. The numerical application is deliberately an assumed engineering case; its inputs are neither experimental observations nor pooled estimates from incompatible studies. Its purpose is to demonstrate the decision mechanism and the measurements needed to test it. The analysis shows how a modest increase in rejected output can outweigh a reduction in process burdens, especially when incoming material carries a substantial footprint. This finding

connects sustainable machining to process capability and provides a practical basis for subsequent comparative shop-floor verification.

2 Manufacturing application and accounting basis

The application is longitudinal turning of a cylindrical steel blank from approximately 60 mm to 50 mm diameter over a 100 mm working length. At an assumed density of 7850 kg/m³, the initial working volume corresponds to approximately 2.22 kg of stock and the removed annulus to 0.678 kg of chips. The specified finished diameter is 50.000 ± 0.025 mm, with arithmetic mean roughness no greater than 1.6 µm. These dimensions and acceptance limits define the example; they are not presented as measurements from an operating plant. Identical material condition, inspection requirements and functional geometry apply to both cooling routes. A two-minute cutting duration per attempted component is assumed, corresponding to assumed usable cutting times of 24 minutes for flood and 40 minutes for MQL. The geometric removal rate averaged over cutting is approximately 43.2 cm³/min. These values define a calculation domain, not an optimised cutting schedule or a qualified production recipe. Figure 1 shows the manufacturing and accounting sequence.

Each comparison concerns a lot of 100 attempted components. Accepted output equals the number that passes the specified inspection, so different yields may produce different accepted counts. Normalisation permits comparison per accepted component; it does not imply that equal starting lots meet the same customer order. Rejected pieces are identified after machining and leave the production boundary for external treatment. The example excludes rework. If rework is available, its electricity, additional tools, fluids and final acceptance must be recorded as a separate route before applying the same output-based accounting.

The boundary includes incoming stock production, allocated machining electricity, MQL air production, net fluid provision and associated treatment, cutting-edge service, and external treatment of rejected pieces. Use-stage performance, delivery to customers and machine manufacture are outside this partial product footprint. Their exclusion assumes that the cooling decision does not change them. No avoided-production credit is assigned to scrap recycling. This convention prevents a rejection from appearing beneficial through an unverified displacement assumption; an alternative allocation would require consistent treatment of both routes [12], [13].

Net flood-fluid demand means concentrate, water and bath replacement allocated to the lot, not the much larger volume repeatedly circulated by the pump. The route-specific fluid-and-chip term in Table 1 is an illustrative aggregate burden; an industrial inventory must disaggregate it. Purchased machine and compressor electricity is mapped to the manufacturer's Scope 2 account, while relevant upstream electricity activities, stock, tools, lubricant and external waste treatment are mapped to their applicable Scope 3 categories [14]. The product calculation uses one consistent electricity factor and does not add these corporate views again.

Table 1
Assumed inputs for the worked turning application. Every numerical entry is illustrative and requires replacement or confirmation using application-specific evidence

Parameter	Flood	MQL	Unit
Attempted components N	100	100	components/lot
Accepted components G	99	98	components/lot
Acceptance yield y	0.99	0.98	fraction
Incoming-stock burden B	4.44	4.44	kg CO_2e/attempt
Non-air electricity e_0	0.30	0.24	kWh/attempt
Delivered free air V	0	1.00	m³/attempt
Compressor electricity s	0.10	0.10	kWh/m³ free air
Electricity factor g	0.40	0.40	kg CO_2e/kWh
Fluid and chip burden U	0.090	0.012	kg CO_2e/attempt
Usable-edge burden C	0.24	0.24	kg CO_2e/edge
Complete components per edge k	12	20	components/edge
Cutting duration t (per component)	2.00	2.00	min/attempt
Rejected-piece treatment d	0.050	0.050	kg CO_2e/reject

Note: B = 2.22 kg stock × 2.00 kg CO_2e/kg stock. U covers net fluid provision and associated treatment plus chip treatment; d covers only additional treatment of rejected pieces. All flows are allocated to completed attempts. V = 0 for flood denotes no incremental MQL air stream; common air demand, if present, belongs in e_0.

3 Methodology

The method combines dimensional accounting, direct substitution and analytical inequalities. It requires no fitted wear model, stochastic experiment or numerical optimisation. The functional unit is one accepted component meeting the drawing requirements. For route j, N denotes attempted components, G accepted components and y acceptance yield. A usable edge completes k whole components before retirement. Where a fixed cutting duration per component is appropriate, k follows from the qualified edge life T and cutting duration t. Both quantities must refer to the same edge and acceptance criterion [17].

$$y_j = \frac{G_j}{N}, \quad k_j = \lfloor \frac{T_j}{t} \rfloor, \quad n_j = \lceil \frac{N}{k_j} \rceil$$

1

An edge is changed between components, and k must be at least one. With a fresh-edge start, n edges are opened. Their unconsumed service u is retained in the tool inventory. The base allocation charges only service used by this lot; a sensitivity case charges all opened edges if their remaining service is unusable. Neither convention additionally charges the same insert at replacement. This allocation does not alter the corporate inventory of tool purchases in the reporting period.

$$u_j = n_j - \frac{N}{k_j}, \quad C_{tool,j} = C_e \left(n_j - u_j\right) = \frac{C_e N}{k_j}$$

2

Here C□ is the burden per usable edge. The component electricity E comprises allocated non-air electricity e_0 and compressed-air electricity sV, where V is delivered free-air volume and s is allocated compressor electricity per unit volume. For measured power P in kilowatts and state duration Δt in seconds, allocation over the lot is:

$$E_j = e_{0j} + sV_j, \quad e_{0j} = \frac{\sum{}_h P_{jh} \Delta\, t_{jh}}{3600 N}$$

3

The power sum includes setup, cutting, idling, extraction and relevant tool changes within the declared boundary. Air already captured by that meter is not added again. The boundary follows machine-tool energy-evaluation principles and state-based machining inventories [18], [19]. The electricity factor g is expressed in kg CO_2e/kWh. Its temporal and upstream coverage must match both routes; the example uses a constant factor. B denotes incoming-stock burden per attempt, U the other fluid-and-chip burden per attempt, and d external treatment burden per rejected piece.

$$A_j = B + U_j + \frac{C_e}{k_j}, \quad I_j = \frac{A_j + gE_j + \left(1 - y_j\right) d}{y_j} = \frac{A_j + gE_j + d}{y_j} - d$$

4

Equation (4) includes stock consumed by rejected pieces and avoids counting their original stock twice. All terms in its numerator are kg CO_2e per attempted component. A compact expression follows by defining A as the non-electricity burden before rejection treatment. The condition that MQL intensity is below flood intensity can then be rearranged without approximating the yield penalty.

$$I_M < I_F \quad \Longleftrightarrow \quad y_M > {y_M}^* = \frac{A_M + gE_M + d}{I_F + d}$$

5

The threshold applies only when its denominator is positive. A value above one means that the stated MQL configuration cannot outperform flood through yield improvement alone. Subsequent rearrangements isolate air volume, electricity factor and edge capacity. Equality represents indifference; procurement or process release requires the strict inequality together with all manufacturing constraints. Uncertainty is evaluated using transparent bounds on shared parameters, retaining the same stock burden and electricity factor in both routes. Endpoint evaluation is justified from monotonicity of the difference, rather than assigning unsupported probability distributions. The resulting ranges are decision bounds, not confidence intervals or evidence of measured population effects. All baseline factors are held constant within each lot. The edge-life allocation assumes identical service across its complete component slots and no premature breakage. If edge age changes energy or rejection substantially, the lot must be divided into recorded age groups and their burdens summed before dividing by total accepted output.

4 Results and discussion

4.1 Baseline accounting and the quality reversal

Under the Table 1 assumptions, flood cooling requires 0.30 kWh per attempted component. MQL requires 0.24 kWh for non-air operation and 0.10 kWh for its 1.00 m³ air supply, giving 0.34 kWh in total. The lower non-air demand therefore becomes a higher total electricity requirement after the compressor is included. At g = 0.40 kg CO_2e/kWh, electricity contributes 0.120 kg CO_2e per attempt under flood cooling and 0.136 under MQL. This arithmetic illustrates the practical concern identified by comparative lubrication assessments: pneumatic support can offset part of the benefit obtained elsewhere [7].

Fluid-and-chip burdens are 0.090 and 0.012 kg CO_2e per attempt, while allocated tooling burdens are 0.020 and 0.012, respectively. Including stock and rejection treatment gives 4.7177 kg CO_2e per accepted flood-cooled component and 4.6949 for MQL. The conditional reduction is 0.0228 kg CO_2e, or 0.48%. At equal 99% yields, the MQL intensity would be 4.6470, approximately 1.50% below flood. The lower MQL yield therefore consumes most of the process advantage. Table 2 reports these comparisons and the specified departures from the baseline.

The yield threshold from Eq. (5) is approximately 97.53%, corresponding to rejection below 2.47%. With 100 attempted components, that continuous boundary requires at least 98 accepted components. A lot delivering 97 accepted pieces crosses the boundary, raising the MQL intensity to 4.7438 kg CO_2e per accepted component. It then exceeds flood by approximately 0.55%. These are conditional arithmetic results, not evidence that MQL causes a particular rejection rate. Experimental reports relating lubrication to wear and surface quality motivate measuring the yield, but cannot supply it for an untested component [5], [6], [20].

Table 2
Calculated scenarios for the assumed application. A negative difference favours MQL; each row changes only the identified baseline quantity, and both routes use the stated electricity factor

Scenario	Flood I	MQL I	MQL − flood	Preferred
Baseline	4.7177	4.6949	-0.0228	MQL
Equal yields yM = 0.99	4.7177	4.6470	-0.0707	MQL
MQL yield yM = 0.97	4.7177	4.7438	+ 0.0261	Flood
MQL air V = 2.00 m³	4.7177	4.7357	+ 0.0180	Flood
MQL capacity k = 6	4.7177	4.7235	+ 0.0058	Flood
Electricity g = 0.05	4.6116	4.5735	-0.0381	MQL
Electricity g = 0.80	4.8389	4.8337	-0.0052	MQL

Note: Intensities and differences are kg CO_2e per accepted component. Values are rounded after calculation; preferences use unrounded results. All rows use service allocation for tools.

4.2 Air demand and electricity switching conditions

Solving the same comparison for MQL air volume produces an operational limit that can be checked with a flow meter and allocated compressor electricity. For positive g and s, the admissible air volume is strictly below:

$$V_M{}^* = \frac{y_M\,(I_F + d) - \left[B + U_M + \frac{C_e}{k_M} + d + ge_{0M}\right]}{gs}$$

6

The baseline threshold is 1.558 m³ per attempted component. Doubling air demand to 2.00 m³ increases MQL intensity to 4.7357 kg CO_2e per accepted component and reverses the ranking. The threshold concerns delivered free air, not compressed pipe volume at an unspecified pressure. Compressor unloading, leakage and distribution losses enter through s according to the allocation boundary. A theoretical compression equation that omits those losses would not establish the achievable operating threshold. If the numerator in Eq. (6) is non-positive, reducing air demand alone cannot establish a strict MQL advantage.

An electricity crossover exists when the two routes have different yield-adjusted electricity demands. For fixed air use, tooling and yield, equality occurs at:

$$g^* = \frac{y_M\,(A_F + d) - y_F\,(A_M + d)}{y_F E_M - y_M E_F}$$

7

For this application, g* is approximately 0.919 kg CO_2e/kWh. MQL is favourable below that value because its reduced non-electricity burden compensates for higher electricity per accepted piece. Figure 2 shows how a one-percentage-point yield change moves the crossover substantially. At 97% MQL yield, the formal crossover is negative, approximately − 0.150 kg CO_2e/kWh. Flood then has the lower intensity throughout the non-negative electricity-factor range. Grid decarbonisation can therefore alter a cooling decision without changing the lubricant delivery system. It does not remove the need to preserve yield. Electricity characterisation also has to match the study boundary; mixing direct-generation and full supply-chain factors would move the crossover for accounting reasons alone [13]. If the denominator in Eq. (7) is zero, the ranking depends solely on the non-electricity terms. A negative denominator reverses the inequality direction. A crossover outside the feasible factor range does not imply an attainable switching point.

4.3 Tool service and finite production lots

Tool performance enters through complete components per usable edge. Holding the other terms fixed gives the minimum required capacity:

$$k_M > \frac{C_e}{y_M\,(I_F + d) - [B + U_M + d + gE_M]}$$

8

The denominator must be positive; otherwise no finite edge capacity satisfies the strict comparison. At the baseline, MQL requires more than 6.992 components per edge, making seven complete components the minimum admissible integer capacity under service allocation. Six components per edge raises intensity to approximately 4.7235 kg CO_2e per accepted part. This result connects a carbon claim to a testable tooling target. Experimental work on sustainable turning and investigations of carbide production support treating edge performance and upstream tooling burden together, while keeping their application-specific values separate [10], [11], [21].

Seven components per edge leaves an advantage of only 0.038 g CO_2e per accepted component. Such a small margin would be overwhelmed by modest measurement or allocation differences. When the entire burden of every opened edge is charged to this 100-component lot for both strategies, the minimum MQL capacity becomes eight. At seven, MQL opens 15 edges and narrowly exceeds flood's intensity. At eight, 13 edges suffice and the ranking favours MQL. Tool-service accounting therefore changes an attainable integer decision, even though the underlying continuous comparison remains consistent.

For 100 attempted components, flood opens nine edges with capacity for 108 components, whereas MQL opens five edges with capacity for 100. Retaining flood's remaining eight component-equivalents yields the base tool allocation of 2.000 kg CO_2e per lot. Charging all nine opened edges gives 2.160 kg CO_2e. The 0.160 difference represents a choice about remaining service, not an observed emission reduction. If the edge is genuinely discarded, its full burden belongs to production; if reused, the

remaining share follows the next lot. The distinction becomes decisive for capacities close to the analytical threshold.

The assumed burden per edge is intentionally not calculated from a universal carbide factor. Published assessments distinguish cemented carbide production, high-speed steel manufacture and the service history of cutting tools [10], [22], [23]. An insert-level inventory should be divided by the usable edges actually available under the selected holder and failure conditions. Nominal edge count alone can overstate useful service when breakage prevents indexing or when damage makes another nominal edge unusable.

4.4 Joint bounds and interpretation

Simultaneous uncertainty was examined with stock burden between 3 and 6 kg CO_2e per attempt, electricity intensity between 0.10 and 0.60 kg CO_2e/kWh, and MQL air volume between 0.5 and 1.5 m³. These are declared scenario bounds. Both cooling routes retain the same stock and electricity values at each evaluation. The MQL-minus-flood difference spans approximately − 0.0595 to + 0.0327 kg CO_2e per accepted component. Because zero lies inside the range, neither route dominates across the stated set. A favourable baseline is therefore insufficient to support an unconditional replacement policy.

The difference increases with stock burden because MQL has the lower assumed acceptance yield. It also increases with air volume when electricity has a positive factor. The lower bound occurs at B = 3, V = 0.5 and g = 0.60; the upper bound occurs at B = 6, V = 1.5 and g = 0.60. Both extrema use the larger electricity factor, but for different reasons. At low air use, MQL has lower electricity per accepted piece; at high air use it has higher electricity per accepted piece. Independent minimum-to-maximum footprint intervals would obscure that shared-parameter structure. Figure 3 provides the corresponding air-and-yield boundary at the baseline electricity factor.

The manufacturing implication is to verify the quantities that can cross a decision boundary before investing in a wider monitoring system. Material intensity amplifies the cost of unsuccessful output; compressor demand and tool service then determine the remaining margin. The method does not rank health effects, water use, machining cost or delivery performance. Comparative assessments of cooling strategies have shown why these dimensions can require separate evaluation [8], [16]. A carbon-favourable operating point supports a cooling decision only when the technical requirements are satisfied and its advantage is stated for the relevant conditions.

5 Industrial verification and transferability

Industrial verification should pair the same component drawing, incoming material condition, insert grade and cutting schedule under the two cooling routes. Production order and edge history must be recorded so that a later batch is not compared with an earlier batch under different machine or material conditions. Qualification should examine the drawing requirements and application-specific surface integrity, rather than using roughness alone as a complete quality surrogate. Turning studies on different

work materials and lubrication arrangements provide examples of measurable responses, but their parameter settings require local qualification [24], [25], [26].

The evidence package should contain attempted and accepted counts, rejection reasons, cutting-edge retirement records, machine electricity, allocated compressor electricity and delivered free-air volume. Fluid records should reconcile opening stock, purchases, make-up, closing stock and waste collections. Time allocation must cover setup and non-cutting states under a consistent rule. Research on machine-tool energy characterisation, process inventories and energy prediction provides methods for organising these measurements [2], [3], [4], [19]. Supplier-specific factors should replace the assumed stock, tool and fluid burdens, with factor coverage documented before combining inventories.

A measured dataset would support uncertainty intervals for yield and energy and a direct test of whether the observed differences remain on one side of the relevant threshold. This paper's 100-component lot is an accounting illustration and supplies no statistical power justification. A subsequent study should determine replication from the difference worth detecting and the variability of its production process. Where speed, wear and air demand change together, paired observations or jointly feasible bounds are required; varying one parameter while silently fixing its dependent quantities can produce an unattainable operating point. Energy-oriented turning models already demonstrate that the objective function and tool-life relationship influence the chosen cutting conditions [27], [28]. Those relationships should be preserved when the present cooling thresholds are tested.

Transfer to other operations requires an explicit inventory update. Nanofluid MQL investigations in AISI 1045 and S235JR turning show why lubricant formulation must remain part of the treatment definition [29], [30]. Work on ultrasonic-assisted turning likewise identifies additional auxiliary equipment whose electricity changes environmental rankings [31]. These findings cannot be treated as measurements of conventional MQL under the present assumptions. The immediate industrial contribution is a set of observable conditions: qualified output, air demand below its threshold and sufficient edge capacity within a consistent footprint boundary. The inequalities remain useful when measured values differ from the example because they identify why the preferred route changes.

Recent multi-criteria research on Inconel 600 compares cooling methods through cutting forces, roughness and temperature [32]. The present method complements such ranking approaches by exposing the carbon boundary per accepted component; it does not replace their technical assessments. It also requires a declared decision margin. A plant should compare the distance from the threshold with the uncertainty of its measurements before claiming a dependable saving. Testing the calculated conditions against matched production lots, including retained tool service and rejected stock, is the next substantive research step. Until then, the numerical application demonstrates the method's operation and its boundary conditions.

6 Conclusion

Cooling selection for precision turning should be evaluated against accepted output, with compressed air, net fluid demand and cutting-edge service included once within a consistent carbon boundary. This study derived explicit yield, air-volume, electricity and tooling thresholds that connect an environmental comparison to quantities available from production records. In the assumed steel-turning application, MQL reduced carbon intensity by 0.48% at the baseline, but increasing rejection from 2% to 3% reversed the ranking. The admissible air demand was below 1.558 m^3 per attempted component, with seven components per edge required under service allocation and eight when all opened edges were charged to the lot. These values describe the stated case and are not experimentally validated performance claims. Joint parameter bounds crossed the point of indifference, showing why a favourable nominal result cannot establish universal superiority. The practical contribution is a transparent method for determining what must be measured and what operating margin must be preserved before a cooling change is justified. Industrial verification should replace the assumed inventories with matched machining observations and supplier evidence, while retaining equivalent component qualification and explicit treatment of rejected output.

Declarations

Data availability.

All assumed inputs and analytical relationships required to reproduce the worked application are included in the article. No new experimental measurements or human-participant data were collected.

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Figures

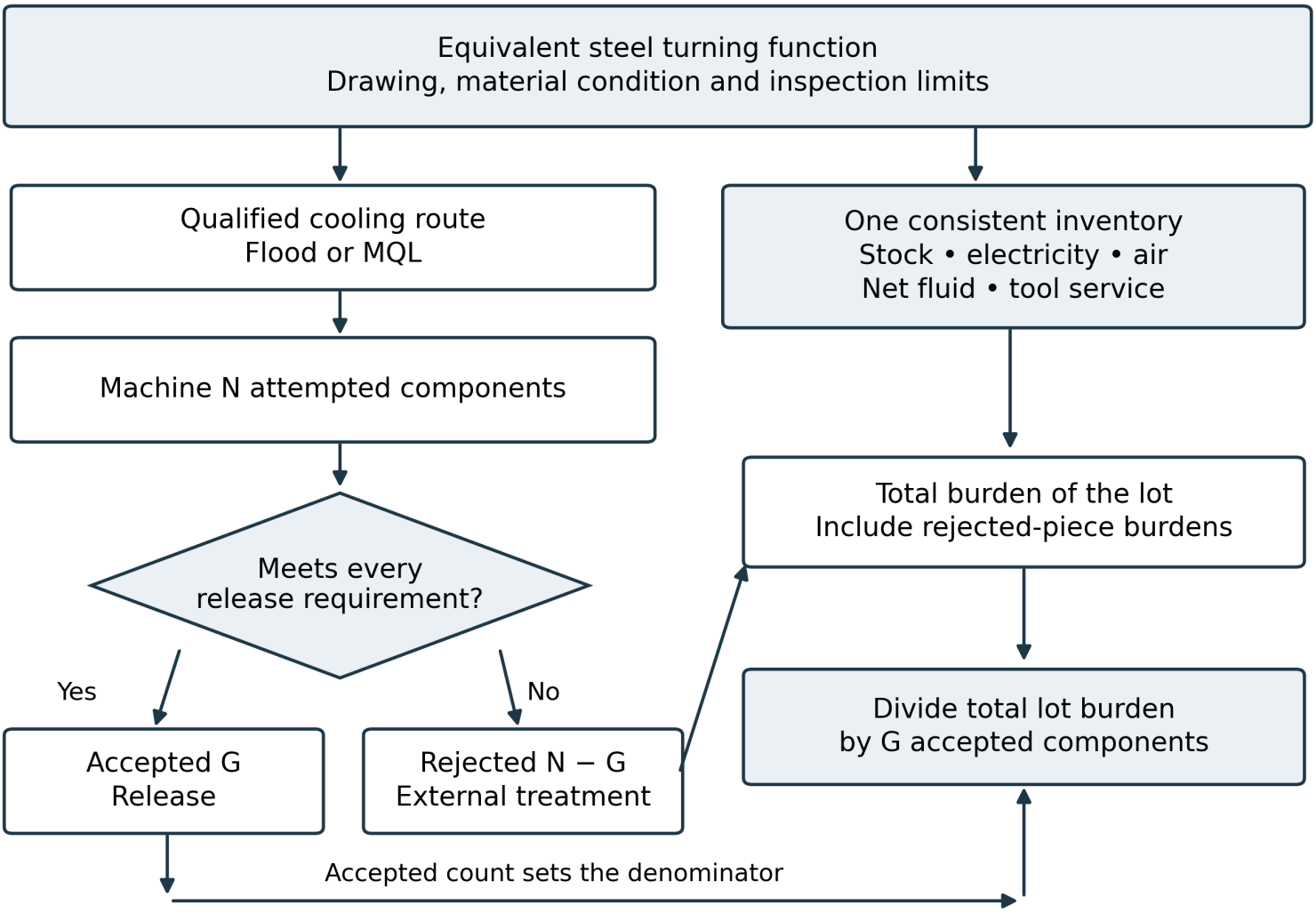


Figure 1

Manufacturing eligibility and carbon accounting for the defined turning function. Inspection separates accepted and rejected output before product release; all burdens remain assigned to the attempted lot

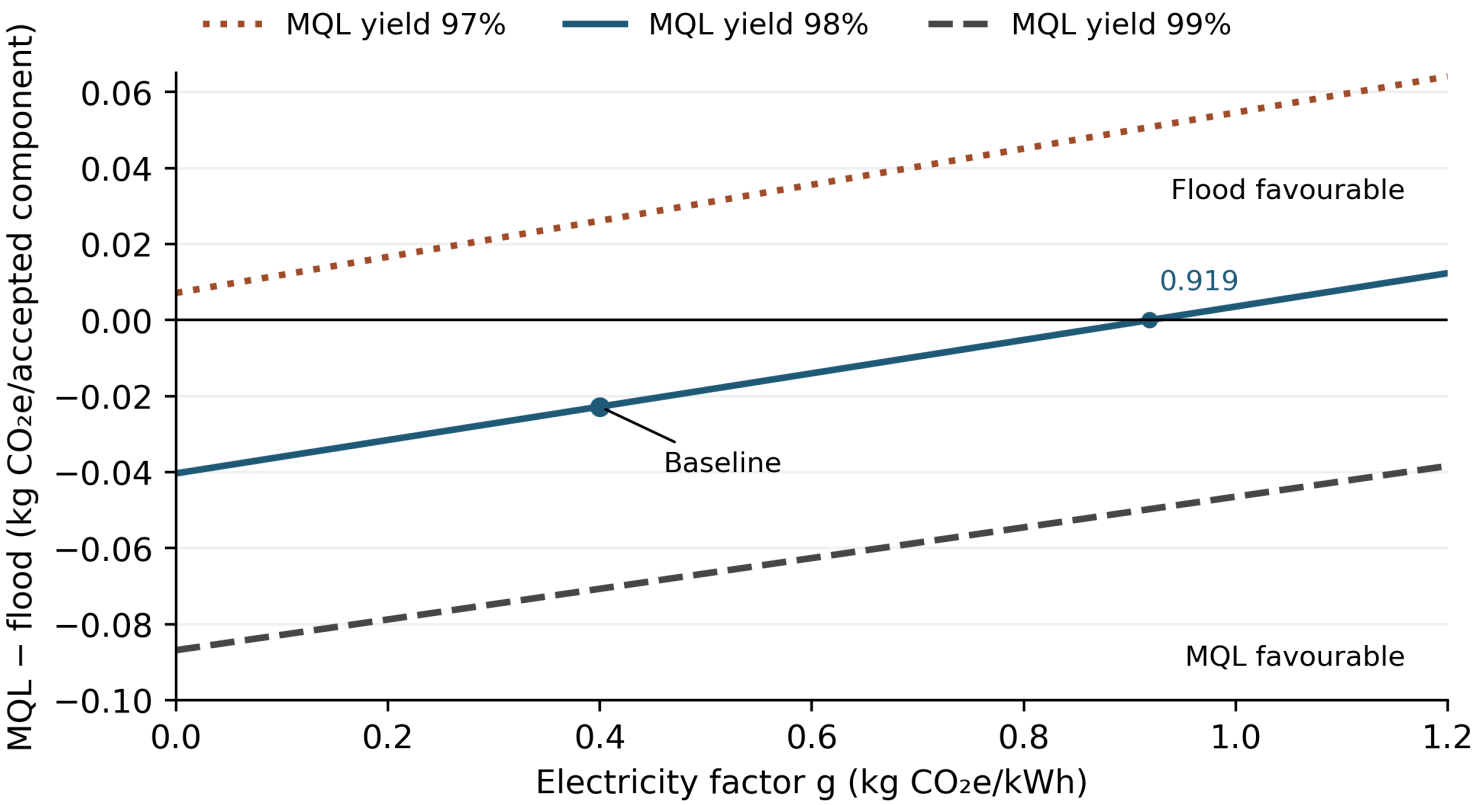


Figure 2

Calculated carbon difference between MQL and flood cooling as electricity intensity changes. Curves use the assumed inputs and selected MQL yields; negative values favour MQL and marked crossings denote equal intensities

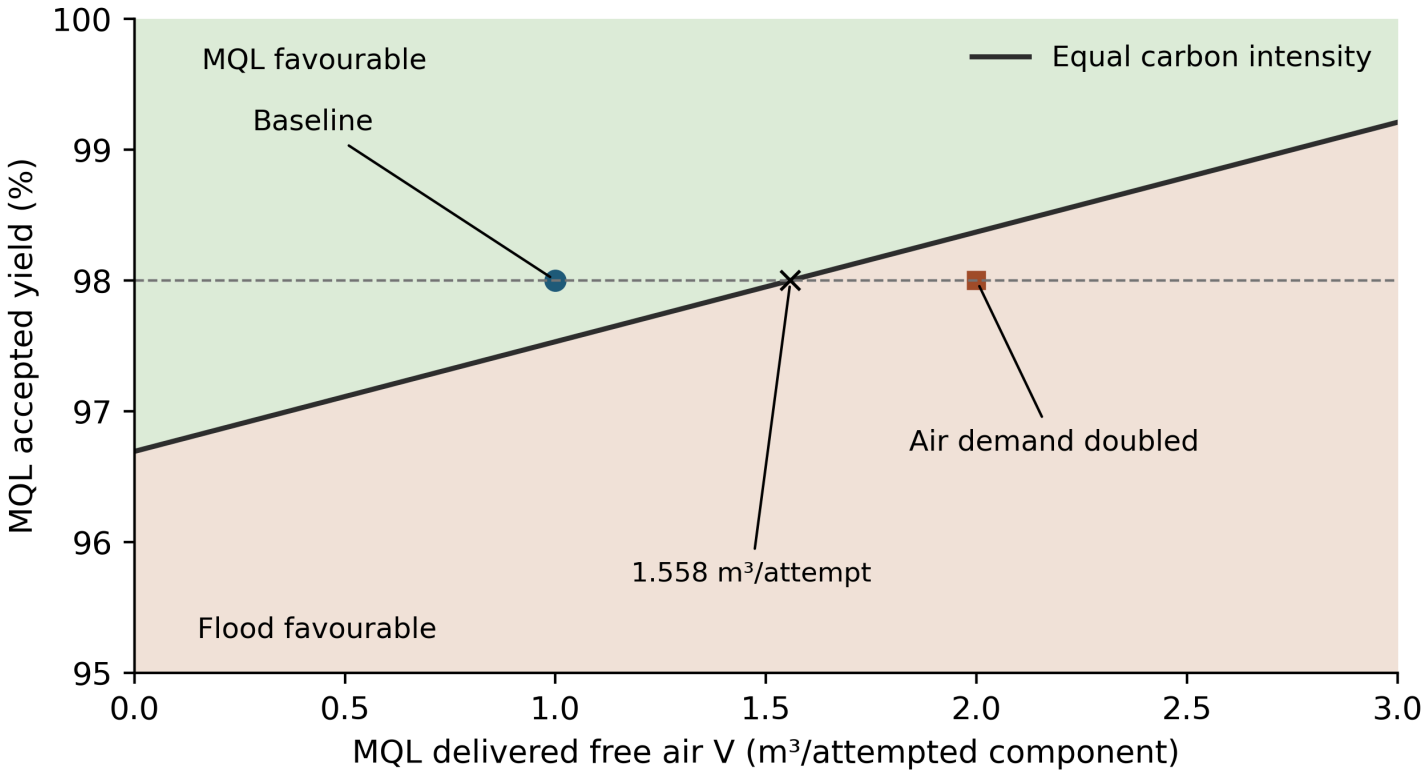


Figure 3

Calculated air and yield decision boundary at the baseline electricity factor and tooling capacities. The shaded regions identify the preferred route under the assumed inventory; the baseline and adverse air scenario are marked