



Research article

Multi-level shipbuilding standard man-hours calculation model for based on four-dimensional interim product features

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Appendix A. Standard Comparison of Mathematical Symbols and Parameters

Note: This appendix summarizes all calibrated parameters that are not raw data (i.e., parameters not directly extracted from the shipyard DAP drawings, the PWBS assembly database or on-site measured ledgers). The physical meaning, hosting formula, typical value, and calibration basis of each parameter are listed item by item according to category. Raw data (such as plate thickness, weld length, material grade, measured welding current and voltage) are directly taken from the shipyard design system and process documents, and are not repeated here.

A.1 Four-Dimensional Feature Correction Parameters

α_j (weight coefficient of the four-dimensional features): used to measure the relative importance of the stage, type, zone and system dimensions in the overall man-hour impact. Location: Eq. (1). Typical value: $\alpha_j = 0.25$ ($j = 1, 2, 3, 4$). Calibration source: set according to the equal-weight allocation principle of Group Technology Theory (GTT); used as the baseline when the shipyard lacks sufficient historical man-hour data, and can be dynamically corrected by the entropy weight method or principal component analysis when sufficient data are available.

$F_{\max}$ (endpoint value of the welding posture impact factor): the extreme difficulty factor in the Logistic model. Location: Eq. (2). Typical value: $F_{\max} = 2.19$. Calibration source: calibrated by normalizing the extreme %MVIC load of core muscle groups measured by sEMG under the overhead welding posture.

k (steepness coefficient of the Logistic curve): controls the growth rate of the S-curve. Location: Eq. (2). Typical value: $k = 1.50$. Calibration source: referring to Logistic fitting empirical values in the machining field, and verified with actual shipyard welding man-hour data.

x_0 (growth inflection complexity): the normalized complexity parameter corresponding to the growth inflection point of the Logistic curve. Location: Eq. (2). Typical value: $x_0 = 1.10$. Calibration source: determined by iterative trial calculation of the median load between flat and overhead welding.

x (welding posture complexity parameter): the normalized difficulty level of the four welding postures (flat, vertical, horizontal, overhead). Location: Eq. (2). Typical value: $x = 1, 2, 3, 4$. Calibration source: according to the four-level equidistant welding difficulty standard of the shipbuilding industry (corresponding to the welding position mapping rules of GB/T 19867.1).

$\beta_{(1, \text{flat})}$ (flat welding impact factor): the type-dimension man-hour amplification factor corresponding to flat welding. Location: Eq. (2). Typical value: 1.01. Calibration source: obtained by substituting $x = 1$ into Eq. (2).

$\beta_{(1, \text{vertical})}$ (vertical welding impact factor): the type-dimension man-hour amplification factor corresponding to vertical welding. Location: Eq. (2). Typical value: 1.32. Calibration source: obtained by substituting $x = 2$ into Eq. (2).

$\beta_{(1, \text{horizontal})}$ (horizontal welding impact factor): the type-dimension man-hour amplification factor corresponding to horizontal welding. Location: Eq. (2). Typical value: 1.78. Calibration source: obtained by substituting $x = 3$ into Eq. (2).

$\beta_{(1, \text{overhead})}$ (overhead welding impact factor): the type-dimension man-hour amplification factor corresponding to overhead welding. Location: Eq. (2). Typical value: 2.19. Calibration source: obtained by substituting $x = 4$ into Eq. (2).

a_{zone} (zone exponential model coefficient): the coefficient term of the zone-dimension exponential growth model $F(x) = ae^{bx} + c$. Location: Section 4.1(2). Typical value: 0.35. Calibration source: determined by exponential regression fitting of 5-level spatial complexity measured data (superstructure, cargo hold, engine room, bow, stern).

b_{zone} (zone exponential model exponent): the exponent term of the zone-dimension exponential growth model. Location: Section 4.1(2). Typical value: 0.35. Calibration source: same as above, by exponential regression fitting of the 5-level data from superstructure to stern.

c_{zone} (zone exponential model constant): the constant term of the zone-dimension exponential growth model. Location: Section 4.1(2). Typical value: 0.50. Calibration source: same as above, by exponential regression fitting of the 5-level data from superstructure to stern.

$F_{\text{max, system}}$ (system Logistic endpoint value): the extreme difficulty factor of the system-dimension Logistic model. Location: Section 4.1(2). Typical value: 2.85. Calibration source: determined by Logistic regression fitting of 4-level process precision data (conventional structure, electrical, propulsion, power).

k_{system} (system Logistic steepness coefficient): the growth rate coefficient of the system-dimension Logistic model. Location: Section 4.1(2). Typical value: 1.20. Calibration source: same as above, by Logistic regression fitting of the 4-level data from structure to power.

$x_{0, \text{system}}$ (system Logistic inflection point): the growth inflection point of the system-dimension Logistic model. Location: Section 4.1(2). Typical value: 1.50. Calibration source: same as above, by Logistic regression fitting of the 4-level data from structure to power.

a_{stage} (stage polynomial quadratic coefficient): the quadratic term coefficient of the stage-dimension quadratic polynomial $F(x) = ax^2 + bx + c$. Location: Section 4.1(2). Typical value: 0.033. Calibration source: determined by polynomial regression fitting of 7-level integration data (part machining, component assembly, block fabrication, grand assembly, erection, quay outfitting, sea trial delivery).

b_{stage} (stage polynomial linear coefficient): the linear term coefficient of the stage-dimension quadratic polynomial. Location: Section 4.1(2). Typical value: 0.011. Calibration source: same as above, by polynomial regression fitting of the 7-level data from part to erection.

c_{stage} (stage polynomial constant term): the constant term of the stage-dimension quadratic polynomial. Location: Section 4.1(2). Typical value: 0.956. Calibration source: same as above, by polynomial regression fitting of the 7-level data from part to erection.

A.2 Personnel Allowance Parameters

k_i (senior skill level benchmark coefficient): the benchmark man-hour efficiency coefficient corresponding to the senior welder skill level. Location: Eq. (5). Typical value: 1.00. Calibration source: shipyard Welder Skill Rating Standard and man-hour difficulty coefficient mapping rules in related literature.

k_i (advanced skill level benchmark coefficient): the benchmark man-hour efficiency coefficient corresponding to the advanced welder skill level. Location: Eq. (5). Typical value: 1.10. Calibration source: same as above, according to the shipyard Welder Skill Rating Standard and related literature.

k_i (intermediate skill level benchmark coefficient): the benchmark man-hour efficiency coefficient corresponding to the intermediate welder skill level. Location: Eq. (5). Typical value: 1.30. Calibration source: same as above, according to the shipyard Welder Skill Rating Standard and related literature.

k_i (junior skill level benchmark coefficient): the benchmark man-hour efficiency coefficient corresponding to the junior welder skill level. Location: Eq. (5). Typical value: 1.60. Calibration source: same as above, according to the shipyard Welder Skill Rating Standard and related literature.

α (skill marginal nonlinear amplification parameter): the nonlinear amplification exponent reflecting the marginal efficiency advantage of highly skilled workers. Location: Eq. (5). Typical value: $\alpha = 0.80$. Calibration source: calibrated by nonlinear least-squares regression on historical team man-hour data of the shipyard.

λ (experience gain limit coefficient): controls the asymptotic upper limit of efficiency improvement by working years. Location: Eq. (6). Typical value: $\lambda = 0.30$. Calibration source: determined by fitting the asymptote of the working-years vs efficiency curve from historical shipyard data.

μ (experience decay rate coefficient): controls the decay rate of efficiency improvement by working years. Location: Eq. (6). Typical value: $\mu = 0.15$. Calibration source: calibrated by logarithmic regression on historical shipyard data together with λ .

q_{max} (qualification upper limit standard): the upper limit of the total number of mandatory and value-added qualifications of a team. Location: Eq. (7). Typical value: $q_{\text{max}} = 10$. Calibration source: determined according to the shipyard Post Qualification Management Measures and the mandatory requirements of IMO and classification societies.

η_1 (mandatory qualification weight coefficient): the contribution weight of mandatory qualifications to the man-hour allowance rate. Location: Eq. (7). Typical value: $\eta_1 = 0.15$. Calibration

source: determined by AHP expert scoring or multiple regression of historical man-hour deviations.

η_2 (value-added qualification weight coefficient): the contribution weight of value-added qualifications to the man-hour allowance rate. Location: Eq. (7). Typical value: $\eta_2 = 0.05$. Calibration source: same as above, by AHP expert scoring or multiple regression of historical man-hour deviations.

β_0 (personnel allowance regression intercept): the intercept term of the personnel allowance multiple regression model. Location: Eq. (10). Typical value: $\beta_0 = 0.95$. Calibration source: calibrated by multiple linear regression (with L2 regularization) on historical team feature vs man-hour deviation samples.

β_1 (skill feature regression weight): the regression weight of the skill feature vector in the personnel allowance model. Location: Eq. (10). Typical value: 0.20. Calibration source: same as above, by multiple regression on historical team feature vs man-hour deviation samples.

β_2 (working-years feature regression weight): the regression weight of the working-years feature vector in the personnel allowance model. Location: Eq. (10). Typical value: 0.30. Calibration source: same as above, by multiple regression on historical team feature vs man-hour deviation samples.

β_3 (qualification feature regression weight): the regression weight of the qualification feature vector in the personnel allowance model. Location: Eq. (10). Typical value: 0.10. Calibration source: same as above, by multiple regression on historical team feature vs man-hour deviation samples.

γ (quadratic regularization suppression coefficient): the L2 regularization coefficient of the personnel allowance regression model to prevent overfitting. Location: Eq. (10). Typical value: $\gamma = 0.05$. Calibration source: determined by 5-fold cross-validation.

A.3 Environmental Allowance Parameters

T_{opt}^- (lower limit of the optimal temperature): the lower limit of the temperature range without workshop operation efficiency loss. Location: Eq. (11). Typical value: 20 °C. Calibration source: determined with reference to GBZ/T 229-2010 Classification of Occupational Hazards at Workplaces and shipyard occupational health standards.

T_{opt}^+ (upper limit of the optimal temperature): the upper limit of the temperature range without workshop operation efficiency loss. Location: Eq. (11). Typical value: 25 °C. Calibration source: same as above, with reference to GBZ/T 229-2010 and shipyard occupational health standards.

a_T (temperature loss impact factor): the nonlinear growth coefficient of efficiency loss after temperature exceeds the optimal range. Location: Eq. (11). Typical value: $a_T = 0.001$. Calibration source: calibrated by segmented regression fitting of measured workshop environment data in different seasons and the corresponding efficiency loss rates.

b_T (temperature loss amplification exponent): the amplification exponent of efficiency loss after temperature exceeds the optimal range ($b_T > 1$). Location: Eq. (11). Typical value: $b_T = 1.50$. Calibration source: same as above, by segmented regression fitting of seasonal workshop environment vs efficiency measured data.

Humidity loss trigger threshold: the critical value at which ambient humidity begins to affect operation efficiency. Location: Eq. (12). Typical value: 70%. Calibration source: determined with reference to shipyard painting/welding workshop environmental management specifications and operation efficiency experiment data.

a_H (humidity loss impact factor): the nonlinear growth coefficient of efficiency loss after humidity exceeds the threshold. Location: Eq. (12). Typical value: $a_H = 0.020$. Calibration source: calibrated by segmented regression fitting of historical environment vs efficiency data of the shipyard.

b_H (humidity loss amplification exponent): the amplification exponent of efficiency loss after humidity exceeds the threshold. Location: Eq. (12). Typical value: $b_H = 1.30$. Calibration source: same as above, by segmented regression fitting of historical environment vs efficiency data.

Noise loss trigger threshold: the critical value at which ambient noise begins to affect operation efficiency. Location: Eq. (13). Typical value: 85 dB. Calibration source: determined with reference to GBZ 2.2-2007 Occupational Exposure Limits for Hazardous Agents in the Workplace (Part 2: Physical Agents).

a_N (noise loss impact factor): the nonlinear growth coefficient of efficiency loss after noise exceeds the threshold. Location: Eq. (13). Typical value: $a_N = 0.001$. Calibration source: calibrated by segmented regression fitting of measured noise data and efficiency loss rates in different operation zones.

b_N (noise loss amplification exponent): the amplification exponent of efficiency loss after noise exceeds the threshold. Location: Eq. (13). Typical value: $b_N = 1.20$. Calibration source: same as above, by segmented regression fitting of measured noise data in different operation zones.

w_T (temperature loss allocation weight): the weight of temperature loss in the comprehensive environmental loss. Location: Eq. (14). Typical value: $w_T = 0.40$. Calibration source: calibrated by multiple regression on historical environment vs efficiency data, satisfying $w_T + w_H + w_N \leq 1$.

w_H (humidity loss allocation weight): the weight of humidity loss in the comprehensive environmental loss. Location: Eq. (14). Typical value: $w_H = 0.30$. Calibration source: same as above, by multiple regression on historical environment vs efficiency data.

w_N (noise loss allocation weight): the weight of noise loss in the comprehensive environmental loss. Location: Eq. (14). Typical value: $w_N = 0.20$. Calibration source: same as above, by multiple regression on historical environment vs efficiency data.

ξ (environmental synergistic interaction coefficient): the loss correction coefficient of the synergistic interaction of multiple environmental factors (temperature, humidity, noise). Location: Eq. (14). Typical value: $\xi = 0.001$. Calibration source: calibrated by fitting the interaction term of multiple environmental factors from historical data.

A.4 Production Physical Quantity Matrix Parameters

p (groove reference thickness): the reference thickness parameter in the cross-sectional area calculation of V-groove welds. Location: Eqs. (17)-(18). Typical value: $p = 2.0$ mm. Calibration source: taken from the Welding Procedure Specification (WPS) or the shipyard standard process library.

η (welding thermal efficiency coefficient): the proportion of electric energy converted into effective heat energy during welding. Location: Eq. (19). Typical value: $\eta = 0.75$. Calibration source: calibrated with reference to measured data of CO₂ gas shielded welding in the Welding Handbook.

v (welding speed): the moving speed of the welding wire along the weld direction. Location: Eq. (19). Typical value: $v = 5.0$ mm/s. Calibration source: determined by typical process parameters of the Welding Procedure Specification (WPS).

ρ_m (welding wire density): the material density of the filler welding wire. Location: Eq. (20). Typical value: $\rho_m = 7.85 \times 10^{-6}$ kg/mm³. Calibration source: material handbook (standard density of

ER50-6 carbon steel welding wire).

C_m (specific heat capacity of welding wire): the specific heat capacity of the filler welding wire material. Location: Eq. (20). Typical value: $C_m = 460 \text{ J/(kg}\cdot\text{°C)}$. Calibration source: material handbook (standard thermophysical parameters of carbon steel welding wire).

ΔT (melting temperature difference of welding wire): the temperature difference required for the welding wire to rise from ambient temperature to melting temperature. Location: Eq. (20). Typical value: $\Delta T = 1500 \text{ °C}$. Calibration source: shipyard process library (the melting point of carbon steel wire is about 1530 °C ; considering preheating of about 30 °C , an approximate value of 1500 °C is taken).

A.5 Standard Man-Hour and Sensitivity Parameters

Γ (man-hour conversion coefficient): the dynamic conversion coefficient from production physical quantity to standard man-hours, matched by stage + trade combination. Location: Eq. (21). Typical value: $\Gamma = 7.7 \times 10^{-5} \text{ h/mm}^3$ (taking grand assembly + welding as an example). Calibration source: obtained by regression fitting of the shipyard historical quota database according to stage + trade combinations, and iteratively updated with process upgrades.

$\Delta X_i/X_i$ (sensitivity disturbance ratio): the relative disturbance amplitude of a single input parameter in the sensitivity analysis. Location: Section 5.2(4). Typical value: $\pm 5\%$. Calibration source: the standard disturbance ratio of the one-factor-at-a-time (OFAT) method commonly used in manufacturing sensitivity analysis.



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