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COTECHMO: The Constructive Technology Development Cost Model

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A detailed analysis of the available literature and the aerospace manufacturing industry has identified a lack of cost estimation techniques to forecast advanced manufacturing technology development effort and hardware cost. To respond, this article presents two parametric 'Constructive Technology Development Cost Models' (COTECHMO). The COTECHMO Resources model is the first and is capable of forecasting aerospace advanced manufacturing technology development effort in person-hours. When statistically analyzed, this model had an outstanding R-squared value of 98% and a high F-value of 106.65, validating model significance. The general model accuracy was tested with 53% of the forecast data falling within 20% of the actual. The second, the COTECHMO Direct Cost model is capable of forecasting the development cost of the aerospace advanced manufacturing technology process hardware. This model had an inferior R-squared value of 76% and an F-value of 5.59, although each was still valid to determine model significance. However, the Direct Cost model accuracy exceeded the Resources model, with 93% of the forecast data falling within 20% of the actual. The article concludes with recommendations for future research, including suggestions for further enhancement of each model verification and validation, within and outside of the supporting organization.

Introduction

Industrialized companies are constantly striving to improve their competitive capability and lower production costs by investing in new or proven aerospace Advanced Manufacturing Technologies (AMTs). Managers are faced with the decision whether to invest in a new AMT when the cost of development is vague and imprecise (Tan, Lim, Platts, & Koay, 2006). This article presents two parametric 'Constructive Technology Development Cost Models' (COTECHMO). The 'COTECHMO Resources' model is the first and is capable of forecasting aerospace AMT development effort in person-hours. The second, the 'COTECHMO Direct Cost' model, is capable of forecasting the development cost in the form of aerospace AMT process hardware. The cost estimation models have been developed using a comprehensive literature review, a detailed evaluation of the aerospace manufacturing industry using interviews, group workshops, and the Wideband Delphi technique. The models have been developed using data from Technology Readiness Levels (TRLs). The original TRL scale was developed by the National Aeronautics and Space Administration (NASA) and consisted of 9 levels of classification, ranging from 'Basic Principles Observed and Reported' (TRL1) to 'Actual System through successful Mission

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Operations' (TRL9) (NASA, 2010). This TRL scale, or equivalent, has now been developed and adapted to suit the aerospace manufacturing industry and is used to harmonize all AMTs under development. Each COTECHMO model forecasts the AMT development effort and cost to TRL6 within the aerospace manufacturing sector. At TRL6, the AMT must be proven to full scale; beyond TRL6, the AMT is transitioned from Research and Technology (R&T) to manufacturing engineering operations (Airbus, 2012; Rolls Royce Plc., 2009). Each COTECHMO model has been verified and validated using 15 AMT historical case studies from the aerospace manufacturing industry. The cases were used to evaluate each model using multiple regression, including a 'model significance/F-test' and a 'sensitivity analysis.' Further validation of each model was provided using prediction level (PRED) values. A PRED value requires the forecast data to fall within a percentage of the actual historical data (Conte, Dunsmore, & Shen, 1986).

Related Research

Existing research has identified the lack of available cost models for forecasting AMT development effort and cost at the initial development stages. AMT cost research so far has focused on forecasting the cost of operating the manufacturing process, not the development effort and cost (Curran, Raghunathan, & Price, 2004). To respond to the existing research limitation, focus was placed on general technology development effort and cost estimation. A further refinement was aimed at technologies that were developed using the TRL. This helped to define existing research from a similar domain and provide a platform to systematically cross reference. This helped solve the AMT development cost estimation problem.

In cost estimation of TRLs within systems engineering, research so far has focused on costing the product for delivery into a system (Shermon, 2009). Further systems engineering research has been conducted by Valerdi (2005) who created a systems engineering cost model. This model was capable of forecasting systems engineering effort in person-months and utilized the TRL as a multiplicative factor. Significant emphasis has been placed on using the TRL as a metric for cost estimation, although no existing research has addressed the cost drivers for technology development (DePasquale & Charania, 2008; Kesseler, 2006). One study utilized the TRL metric to adjust existing commercially available cost estimation models for space programs (Malone, Smoker, Apgar, & Wolfarth, 2011). This study was based on historical development time, although it did not identify the specific cost drivers. Existing commercial tools only estimate development cost as a single element of overall hardware product cost. The TRL is used as part of an assumption to spread this estimated cost over the technology development cycle. Many commercial hardware cost estimation and resource forecasting models are now looking to integrate TRLs as a metric. However, these have not been implemented and are not taken into consideration when specifically analyzing the development of AMTs (Price Systems, 2010; Fischman & Hunt, 2006).

In summary, there have been no specific cost models with associated parameters able to estimate cost of technology development using the TRL. In particular, no existing research has identified the exact cost and effort drivers for development of AMTs. Therefore, there is a need to develop two novel cost models in this area. The models must be capable of forecasting AMT development effort in person-hours and cost of hardware to TRL6.

Research Methodology

The research methodology followed for the development of two COTECHMO parametric forecasting models is illustrated in Figure 1. This was identified from the literature

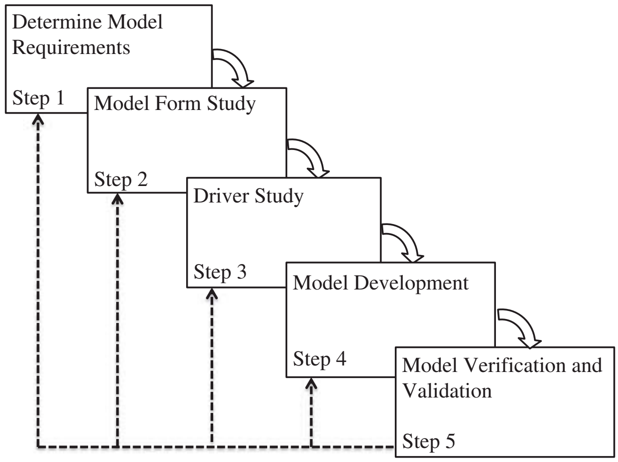

FIGURE 1 Research methodology for COTECHMO development.

and initially validated by industrial experts from aerospace AMT development and the cost estimation community. Initial validation had a combined experience level from AMT development experts of 184 years and leading experts from cost estimation of 220 years. Each stage of the methodology is described in the following:

- **Step 1. Research Methodology to Determine Model Requirements.** Step 1 of the research methodology involved investigation of the industrial requirements and determined the model needs from the aerospace manufacturing organizations. This was performed using interviews and workshops, providing the platform to develop the two parametric models.
- **Step 2. Research Methodology for Model Form Study.** The COTECHMO requirements set by industrial experts in Step 1 of the research methodology formed the model requirements from a manufacturing development perspective. Cost estimation experts were then selected and presented the requirements specified for each model. The final experts directly involved with the development of each COTECHMO equation form are listed in Table 1. The final results from this study are presented in the sections: 'COTECHMO Resources Model Development' and 'COTECHMO Direct Cost Model Development'.

TABLE 1 Cost estimation experts used to determine COTECHMO model forms

Expert number	Organization	Role	Cost estimation experience in years
1	A	Associate Professor (Cost Estimation)	10
2	B	Principle Consultant (Cost Estimation)	29
3	C	Software Development Company Owner	35
4	D	Cost Estimation Research Fellow	11
5	E	Cost Estimation Business Development Manager	20
6	E	Cost Estimation Training and Support Manager	20
7	F	Cost Director	15

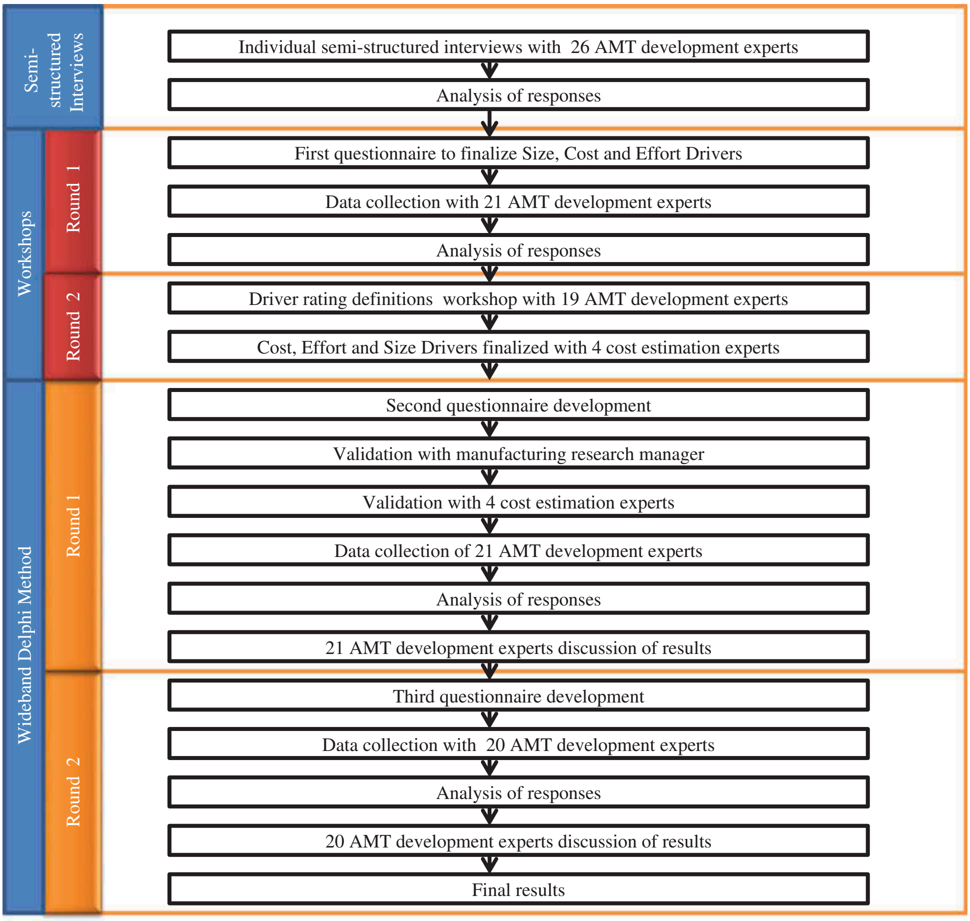

FIGURE 2 COTECHMO driver study.

- **Step 3. Research Methodology for Drivers Study.** Following the results of the model requirements and model form discussed previously, a detailed study was conducted to identify Size, Cost, and Effort Drivers for the COTECHMO Resources and Direct Cost models. This study is illustrated in Figure 2, identifying the stages, including semi-structured interviews, workshops, and the Wideband Delphi process. The Wideband Delphi process was regarded as a crucial element of this research and determined the quantified weighting for Size, Cost, and Effort Drivers for each model. The experience level (in years) of each AMT development expert who contributed to the Wideband Delphi study is listed in Table 2. The final results from this study are presented in the sections: 'COTECHMO Resources Model Development' and 'COTECHMO Direct Cost Model Development'.
- **Step 4. Research Methodology for Model Development.** Each COTECHMO model was developed in Microsoft (MS) Excel. Industry experts were then presented each model and asked to provide enhancement of the user interfaces and overall operation. These final models were then used for forecasting development effort and cost of 15 AMTs, presented later in the 'COTECHMO Case Study' section.

TABLE 2 Experience level in years of participants within the Wideband Delphi study

Round 1		Round 2	
Years of experience	Number of participants	Years of experience	Number of participants
<5	8	<5	8
5–9	5	5–9	4
10–19	6	10–19	6
20–29	1	20–29	1
30+	1	30+	1

- **Step 5. Research Methodology for Model Verification and Validation.** To validate and verify each developed model, multiple regression diagnostics were performed, including a model significance/F-test and a sensitivity analysis. Further verification was provided by evaluating the accuracy of each model using PRED values. The results of this study are presented within the 'COTECHMO Verification' section.

COTECHMO Resources Model Development

To meet the detailed model requirements, a COTECHMO Resources model was developed using the research methodology discussed previously. The model is capable of forecasting AMT development resources (person-hours) to TRL6.

Resources Model Derivation

When evaluating the Resources model overall Cost Estimating Relationship (CER), distinction must be made between Size and Effort Drivers (Effort Multipliers). The two parameters in the model are additive and multiplicative, categorized within Equation (1):

$$PH = A * (Size) * (EM)\,, \tag{1}$$

where:

PH = person-hours (effort in resources);
A = calibration factor derived from historical project data;
$Size$ = measure(s) of functional size of AMT process that has an additive impact on AMT development effort (person-hours);
EM = effort multipliers that impact AMT development effort (person-hours).

Equation (2) is the final COTECHMO Resources model parametric CER and is broken down into 3 Size Drivers (predictors) and 13 Effort Drivers (effort multipliers):

$$PH = A \cdot \left(\sum_k \omega_e \phi_e + \omega_n \phi_n + \omega_d \phi_d \right) \cdot \prod\nolimits_{i-1}^{13} EM_i, \tag{2}$$

where:

PH = person-hours (effort in resources);
A = calibration factor derived from historical project data;
k = number of geometric requirements, number of process steps, number of test pieces;
ω = size driver weighting;
e = easy;
n = nominal;
d = difficult;
$\emptyset$ = size driver count;
EM_i = effort multiplier for the ith effort driver, with the nominal value set at 1.0. Adjacent multipliers constant ratios (geometric progression).

Resources Model Driver Study

Size Drivers. The size drivers form the additive part of the CER presented in Equation (2). These quantify the functional size of the AMT process for its direct manufacturing application. Each size driver represents an output created from an objective measure (i.e. physical size). The size drivers were defined from the detailed driver study presented in Figure 2. These capture the functional size of the AMT process and include: number of geometric requirements, number of process steps, and number of test pieces, each listed and elaborated within Table 3.

Effort Drivers. The Effort Drivers feed into the multiplicative aspect of the CER presented in Equation (2). These are also referred to as Effort Multipliers, from impacting the whole AMT development in a multiplicative configuration. To help assist with the novel effort driver definitions and ratings, each driver was placed into the following themes: Development Team Factors (Table 4), Demonstration and Application Factors (Table 5), Project Factors (Table 6), and a Product Rate Factor (Table 7).

Once each driver was placed into themes, rating scales were applied based on the concept of impact and polarity. The rating scales defined by experts were: Very Low, Low, Nominal, High, and Very High. A rating of Nominal has no impact on the driver with an assigned value of 1.0. Weightings above and below 1.0 were assigned, based on their individual polarity. These values were defined within the two-stage expert driven Wideband Delphi technique, discussed in the proceeding subsection.

TABLE 3 Functional size drivers

Number of Geometric Requirements
The number of requirements taken from the AMT process customer specification. These can be quantified by counting the conceptual application documentation.
Number of Process Steps
The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.
Number of Test Pieces
The number of test pieces required to prove the process capability at full scale, TRL6. This is counted from the customer's application specification.

TABLE 4 Effort drivers for development team factors

TRL Pack Experience
The level of familiarity of the development team from compiling successful Technology Readiness Level development (TRL) documents.
Nominal = Utilized the TRL development documents to successfully transition from one TRL gate to the next.
Product Application Experience
The level of product knowledge for the direct application (e.g., understanding the existing aircraft manual sealant application to develop an automated manufacturing technology solution).
Nominal = Fully familiar with existing product manufacturing.
Process Experience
The level of experience of the development team in the manufacturing process domain (e.g., direct automation development experience).
Nominal = Familiar with the process domain.
Requirements Understanding
The understanding of the requirements from the direct customer (e.g., automated drilling hole requirements for their exact product).
Nominal = Reasonable: some undefined areas.
Supplier Network Availability and Capability
Manufacturing process supplier availability and capability to develop the process.
Nominal = Development experience of a similar process.

TABLE 5 Effort drivers for demonstration and application factors

Datum Complexity
Complexity of datum(s) for the manufacturing process application.
Nominal = Datum(s) with low access restrictions.
Test Piece Material Complexity
Complexity of the test piece material to prove the manufacturing process at full scale application.
Nominal = Medium complexity: material implemented in one or more similar domains of aerospace manufacture.
Installation Complexity
Installation complexity of the manufacturing process to prove at full scale. A highly complex process would consist of many automation equipment installations.
Nominal = Moderately complex: replacement installation procedure similar to the existing process.
Degree of Process Novelty
Manufacturing process novelty for the direct application (e.g., automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain).
Nominal = Process developed, implemented, and proven in one or more non-aerospace domains (e.g., automotive manufacture).

TABLE 6 Effort drivers for project factors

Required Development Schedule
Required delivery from the customer for the development and deployment of the manufacturing process, proven at full scale for the direct application (TRL6). Very low is an accelerated schedule (schedule compression) with very high having a development schedule slower than the nominal.
Nominal = ≥12 months per TRL gate milestone.
Manufacturing Documentation of Requirements
Specific documentation by Manufacturing Engineering for the development enhancement. Legacy (existing) products are typically documented to a higher level when compared to future aircraft manufacture.
Nominal = Legacy product already in manufacture with levels of documentation planned to TRL4-6.
Location Variation of Trials and Tests
Variation of the trials and tests through the development process, to prove the manufacturing process to full scale (TRL6).
Nominal = Location variation of research resources within the same county/state.

TABLE 7 Effort driver for product rate factor

Production Rate Requirements
The required production rate to prove the process at full scale demonstration, TRL6.
Nominal = Between 5 to 10% increase in the existing production rate.

Resources Model Wideband Delphi Results

Size Drivers. Final results from Round 2 of the Wideband Delphi process for each of the Size Driver weightings are listed in Table 8. These feed into the additive aspect of the CER presented in Equation (2).

Effort Drivers. Final results from Round 2 of the Wideband Delphi process for each of the Effort Driver ratings are listed in Table 9. These feed into the multiplicative aspect of the CER presented in Equation (2). The scale's nominal value is set at 1.0, with the polarity depending on the assigned variability for that specific driver. The ratings for each of the Effort Multipliers have been ranked systematically based on their Effort Multiplier Ratios

TABLE 8 Functional size driver weightings from Wideband Delphi round 2

	Relative complexity weights		
Functional size drivers	Easy	Nominal	Difficult
Number of geometric requirements	0.5	1.0	3.0
Number of process steps	1.0	2.0	4.0
Number of test pieces	0.5	1.0	1.5

TABLE 9 Effort driver ratings and effort multipliers from Wideband Delphi round 2

Effort driver name	Very low	Low	Nominal	High	Very high	EMR
Product application experience	1.85	1.36	1.00	0.77	0.60	**3.08**
Degree of process novelty	0.62	0.79	1.00	1.36	1.85	**2.98**
Process experience	1.64	1.28	1.00	0.81	0.65	**2.52**
Test piece material complexity	0.65	0.81	1.00	1.22	1.50	**2.31**
Requirements understanding	1.50	1.22	1.00	0.81	0.65	**2.31**
Manufacturing documentation of requirements	1.50	1.22	1.00	0.81	0.65	**2.31**
TRL pack experience	1.48	1.22	1.00	0.82	0.67	**2.21**
Supplier network availability and capability	1.39	1.18	1.00	0.85	0.72	**1.93**
Installation complexity	0.76	0.87	1.00	1.21	1.47	**1.93**
Location variation of trials and tests	0.76	0.87	1.00	1.21	1.47	**1.93**
Production rate requirements	—	—	1.00	1.37	1.87	**1.87**
Required development schedule	1.66	1.20	1.00	1.13	1.28	**1.29**
Datum complexity	—	—	1.00	1.13	1.28	**1.28**

EMR: Effort Multiplier Ratio.

(EMR). The EMR identifies the variability of the driver and its individual influence on development person-hours.

COTECHMO Direct Cost Model Development

To meet the detailed model requirements, a COTECHMO Direct Cost model was developed using the research methodology. The model is capable of forecasting AMT development Direct (Hardware) Cost to TRL6.

Direct Cost Model Derivation

When evaluating the overall Direct Cost model CER, distinction must be made between the Size and Cost Drivers. The Direct Cost model's equation form is different than the Resources model discussed previously. This model uses additive (physical hardware size) and multiplicative (development complexity), presented in Equation (3):

$$DC = A * (Size) * (CM) \tag{3}$$

where:

DC = direct cost (Euros);
A = calibration factor derived from historical project data;
$Size$ = measure of physical hardware size of the AMT process in volume;
CM = cost multipliers that impact AMT development direct cost.

Equation (4) is the final COTECHMO Direct Cost parametric CER and is broken down into 1 Size Driver (predictor) and 13 Cost Drivers (Cost Multipliers):

$$DC = A \cdot (x, y, z) \cdot \prod_{i-1}^{13} CD_i, \tag{4}$$

where:

DC = direct cost (Euros);
A = calibration factor derived from historical project data;
x = width of the AMT process hardware;
y = length of the AMT process hardware;
z = height of AMT process hardware;
CD_i = cost multiplier for the ith cost driver with nominal set at 1.0.

Direct Cost Model Driver Study

Size Driver. The model consists of one size driver and forms the additive part of the CER presented in Equation (4). This driver quantifies the physical volume of the AMT process hardware for its assigned manufacturing application. The size driver captures the volume from the documentation requirements at the initial conceptual stages, TRL1-2. The physical size driver development was more straightforward than the functional sizing technique used for the Resources model. This driver does not use complexity weights, just a measure of the AMT process volume. However, care has been taken to ensure all complexities have been captured within each of the 13 cost multipliers.

Cost Drivers. The Cost Drivers feed into the multiplicative aspect of the CER presented in Equation (4). These are also referred to as Cost Multipliers, from impacting the whole AMT development in a multiplicative configuration. To help assist with the novel cost driver definitions and ratings, each driver was placed into four themes: Process Primary Factors (Table 10), Secondary Process Factors (Table 11), Process External Factors (Table 12), and a Product Rate Factor (Table 13).

Direct Cost Model Wideband Delphi Results

Size Driver. The Direct Cost model size driver captures the physical volume of the AMT process and does not require a quantified weighting. Therefore, this driver has been eliminated from the Wideband Delphi study.

Cost Drivers. The final results from Round 2 of the Wideband Delphi process for each of the cost driver ratings are listed in Table 14. These feed into the multiplicative aspect of the CER presented in Equation (4). The nominal value of the scale is set at 1.0, with the polarity depending on the assigned variability for that specific driver. The quantified ratings for each of the Cost Multipliers have been systematically listed based on their Cost Multiplier Ratios (CMR). The CMR identifies the variability of the driver and its individual influence on AMT development direct cost.

COTECHMO Case Study

To validate and verify the accuracy of each COTECHMO model, resources (person-hours) and direct (hardware) cost estimation of 15 AMTs was performed. Each of the AMTs had been developed within a leading aerospace manufacturing organization using the TRL. At TRL6, the AMT is developed to full scale and ready for delivery into manufacturing

TABLE 10 Cost drivers for primary process factors

Number of Geometric Accuracy Requirements
The number of requirements taken from the manufacturing process customer specification. These can be quantified by counting the conceptual application documentation.
Nominal = three or more geometric accuracy requirements replicating the existing process; none above existing process accuracy.

Number of Process Steps
The number of process steps can be counted from the customer application specification to prove the process at full scale.
Nominal = three or more process steps replicating existing complexity; no process steps above existing complexity.

Process Capability Requirements
Process capability (Cpk) requirements for the direct application, identified within the process requirements specification.
Nominal = Process capability $\geq$ 1.33 Cpk.

Degree of Process Novelty
Manufacturing process novelty for the direct application (e.g., automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain).
Nominal = Process developed, implemented, and proven in one or more non-aerospace domain (e.g., automotive manufacture).

Installation Complexity
Installation complexity of the manufacturing process to prove at full scale. A highly complex process would consist of many automation equipment installations.
Nominal = Moderately complex: replacement installation procedure similar to the existing process.

operations. Each model's calibration and the final estimated results are presented in the proceeding subsections.

Resources Model

The first stage of performing a COTECHMO Resources (person-hours) forecast involved capturing data from historical AMT developments to TRL6. The mean TRL6 development data for the 15 AMTs equaled 5,374 person-hours. The next stage involved calibrating the model's size driver, by calculating the mean functional size for the 15 AMTs. The total functional size for the 15 AMTs was 972.5, so 972.5 divided by 15 equals 64.83. Therefore, to equate the mean output of 5,374 person-hours with nominal complexity, the calibration constant is 82.93. This forms the final calibration factor (A) detailed earlier within Equation (2). Figure 3 illustrates the summary of this data calibration exercise. Please note this diagram is for illustration purposes only and is not to scale.

The next step involved the users operating the developed MS Excel Resources model, with the interface illustrated in Figure 4. Within the interface, cells highlighted yellow require data input. Users counted the functional size requirements and rated the effort drivers for their AMT(s). For the intention of this case study, the model was utilized to forecast development person-hours for the 15 AMTs, using the aligned expert(s). The final

TABLE 11 Cost drivers for secondary process factors

Manufacturing Environment Requirements
Temperature requirements to prove the process accuracy at full scale application.
Nominal = Standardized test and verification procedure.
Automation Level Requirements
The level and novelty of the automated control used within the process.
Nominal = Process requires a fully automated control, proven within the same domain.
Test Piece Material Complexity
Complexity of the test piece material, to prove the manufacturing process at full scale application.
Nominal = Medium complexity: material implemented in one or more coherent domain of aerospace manufacture.
Process Test and Verification Requirements
Process test and verification requirements to prove the manufacturing process at full scale demonstration, TRL6.
Nominal = Standardized test and verification procedure for a similar manufacturing process.

TABLE 12 Cost drivers for external requirement factors

Metrology Requirements
Metrology monitoring requirements to prove the manufacturing process and meet the customer requirements (e.g., process capability).
Nominal = Replication of the existing process human factor requirements.
Human Factor Requirements
Human factor requirements of the manufacturing process to meet the customer requirements (e.g., safety cell around the process to comply with human factor legislation).
Nominal = Replication of existing process human factor requirements.
Tooling Requirements
The tooling and fixture requirements to support the manufacturing process.
Nominal = Existing complexity: tooling and fixture requirements replicating the existing process.

TABLE 13 Cost driver for product rate factor

Production Rate Requirements
The required production rate to prove the process at full scale demonstration, TRL6.
Nominal = Between 5 to 10% increase in the existing production rate.

estimated AMT development person-hours are listed with the actual historical values, presented in Table 15. This data is then used to perform a detailed verification of the Resources model, presented within the proceeding 'COTECHMO Verification' section.

TABLE 14 Cost driver ratings and cost multipliers finalized from Wideband Delphi round 2

Cost driver name	Very low	Low	Nominal	High	Very high	CMR
Number of geometric accuracy requirements	0.40	0.60	1.00	1.60	1.87	**4.67**
Degree of process novelty	0.50	0.70	1.00	1.49	1.90	**3.80**
Automation level requirements	0.60	0.81	1.00	1.60	1.90	**3.17**
Tooling requirements	0.55	0.70	1.00	1.30	1.60	**2.91**
Number of process steps	0.67	0.82	1.00	1.48	1.85	**2.76**
Process capability requirements	0.67	0.82	1.00	1.48	1.85	**2.76**
Test piece material complexity	0.60	0.72	1.00	1.18	1.39	**2.32**
Metrology requirements	0.60	0.72	1.00	1.18	1.39	**2.32**
Production rate requirements	—	—	1.00	1.40	1.92	**1.92**
Human factors requirements	0.72	0.85	1.00	1.10	1.20	**1.67**
Manufacturing environment requirements	0.81	0.90	1.00	1.10	1.27	**1.57**
Installation complexity	0.81	0.90	1.00	1.10	1.27	**1.57**
Process test and verification requirements	0.81	0.90	1.00	1.10	1.27	**1.57**

CMR = Cost Multiplier Ratio.

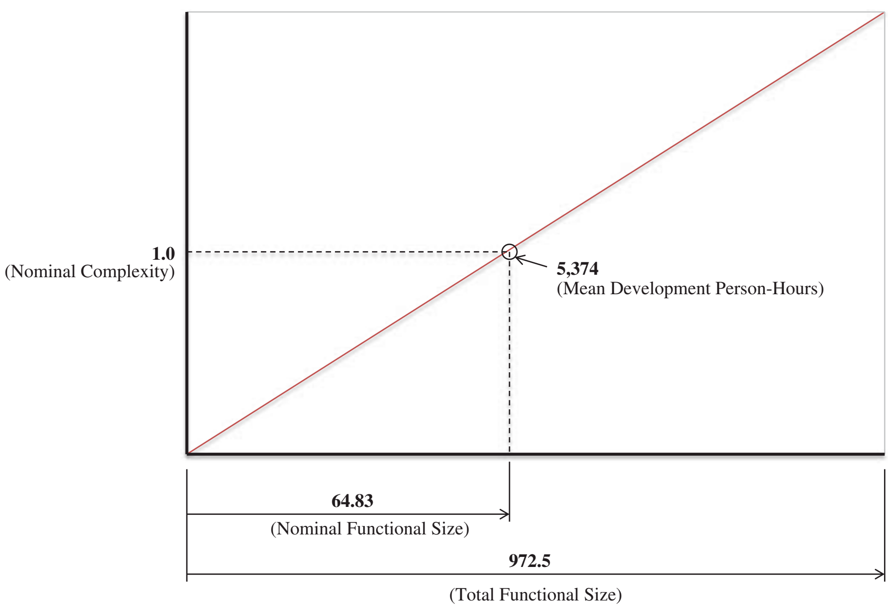

FIGURE 3 COTECHMO resources calibration.

Direct Cost Model

Following the Resources model discussed previously, the first stage of performing a COTECHMO Direct (Hardware) Cost forecast involved capturing data from AMT developments to TRL6. The mean TRL6 development data for the 15 AMTs equaled

	Complexity of Requirement		
Functional Size	**Easy**	**Nominal**	**Difficult**
# Geometric Requirements	0	0	0
# Process Steps	0	0	0
# Test Pieces	0	0	0

Effort Drivers		
Development Team Factors	**Rating**	
TRL Pack Experience	**N**	1.00
Product Application Experience	**N**	1.00
Process Experience	**N**	1.00
Requirements Understanding	**N**	1.00
Supplier Network Availability and Capability	**N**	1.00
Demonstration & Application Factors	**Rating**	
Datum Complexity	**N**	1.00
Test Piece Material Complexity	**N**	1.00
Installation Complexity	**N**	1.00
Degree of Process Novelty	**N**	1.00
Project Factors	**Rating**	
Required Development Schedule	**N**	1.00
Manufacturing Documentation of Requirements	**N**	1.00
Location Variation of Trials and Tests	**N**	1.00
Product Rate Factor	**Rating**	
Production Rate Requirements	**N**	1.00
		1.00 Composite Effort Multiplier

AMT Development Person-hours 0

FIGURE 4 COTECHMO Resources model MS Excel user interface.

TABLE 15 COTECHMO Resources model case study data

Case number	Resources actual (person-hours)	Resources estimated (person-hours)
1	20,803	19,332
2	15,000	18,317
3	7,500	5,921
4	6,597	7,872
5	6,400	7,262
6	5,200	4,791
7	3,700	3,326
8	2,600	2,348
9	2,400	2,559
10	2,363	3,598
11	2,000	2,497
12	1,930	1,725
13	1,735	2,571
14	1,375	1,747
15	1,005	1,273

979,942 Euros. The next stage involved calibrating the model's size driver by calculating the mean physical size of the AMT hardware for the 15 AMTs. The total hardware size for the 15 AMT historical cases was 5,498.8 m^3; thus, 5,498.8 m^3 divided by 15 equals 366.6 m^3. Therefore, to equate the mean output of 979,942 Euros with nominal complexity,

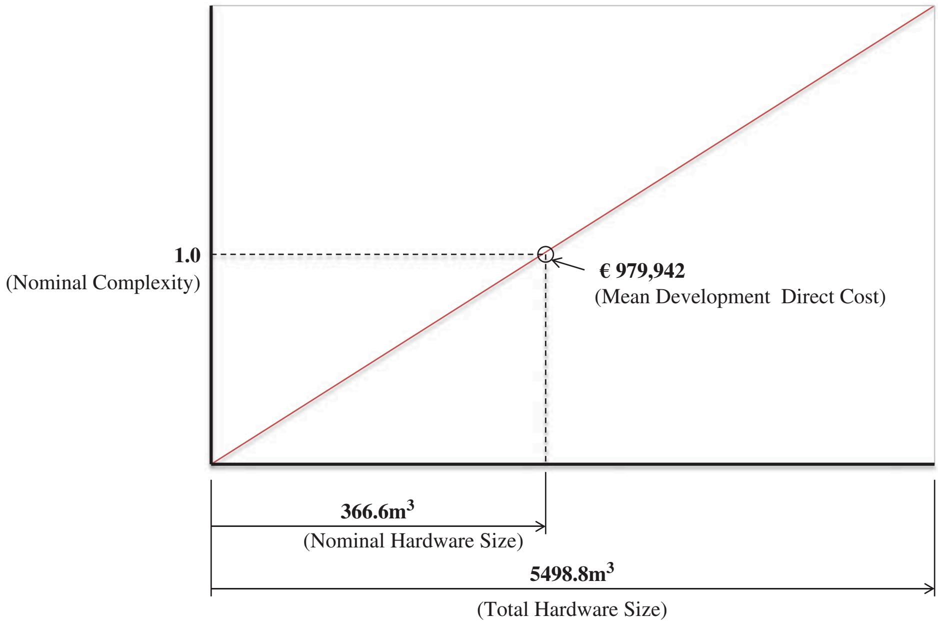

FIGURE 5 COTECHMO Direct Cost calibration.

Required Size of AMT Process	**Width**	**Height**	**Length**
Process Hardware Size (Meters)	0	0	0

Cost Drivers		
Primary Process Factors	**Rating**	
# Geometric Accuracy Requirements	**N**	1.00
# Process Steps	**N**	1.00
Process Capability Requirements	**N**	1.00
Degree of Process Novelty	**N**	1.00
Installation Complexity	**N**	1.00
Secondary Process Factors	**Rating**	
Manufacturing Environment Requirements	**N**	1.00
Automation Level Requirements	**N**	1.00
Test Piece Material Complexity	**N**	1.00
Process Test and Verification Requirements	**N**	1.00
External Process Factors	**Rating**	
Metrology Requirements	**N**	1.00
Human Factors Requirements	**N**	1.00
Tooling Requirements	**N**	1.00
Product Rate Factor	**Rating**	
Production Rate Requirements	**N**	1.00
	Composite Cost Multiplier	1.00
	AMT Development Direct Cost	**€ 0**

FIGURE 6 COTECHMO Direct Cost model MS Excel user interface.

the calibration constant is 2,673.4. This forms the final calibration factor (A) presented earlier in Equation (4). Figure 5 illustrates the summary of this data calibration exercise. Please note this diagram is for illustration purposes only and is not to scale.

TABLE 16 COTECHMO Direct Cost model case study data

Case number	Direct costs actual (Euros)	Direct costs estimated (Euros)
1	2, 600, 000	2, 571, 462
2	2, 400, 000	2, 661, 120
3	2, 200, 000	2, 076, 878
4	1, 122, 129	1, 072, 707
5	1, 078, 000	1, 276, 060
6	687, 000	629, 074
7	659, 000	695, 545
8	651, 000	591, 738
9	650, 000	678, 017
10	591, 000	610, 420
11	570, 000	619, 845
12	430, 000	468, 751
13	420, 000	396, 427
14	391, 000	319, 065
15	250, 000	305, 729

The next step involved the users operating the developed MS Excel Direct Cost model, with the interface illustrated in Figure 6. Within the interface, cells highlighted yellow require data input. Users then quantified the physical size of the AMT process hardware and rated the cost drivers for their AMT(s). Following the Resources model, the model was then utilized to forecast development direct cost for the 15 AMTs, using the aligned expert(s). The final estimated AMT development direct costs are listed with the actual historical values, presented in Table 16. Following the Resources model, this data is then used to perform a detailed verification of the Direct Cost model, presented within the proceeding 'COTECHMO Verification' section.

COTECHMO Verification

The case study presented previously provided the data to perform a detailed verification of the Resources model and Direct Cost model. The results are presented in the proceeding subsections.

Resources Model Verification

The COTECHMO Resources model can be characterized by a multiple regression model. The response of the model is development person-hours and the predictors are the 16 drivers that have an influence on aerospace AMT development effort. The estimation of a linear application was predicted by the Cost Estimation experts listed in Table 1 and utilized the Ordinary Least Squares (OLS) criterion. This aims to define a simple linear regression mean function and determine the relationship between the 16 AMT development drivers (independent variables), with the AMT development person-hours (dependent variable). The multiple regression model is written in the form:

$$\gamma_t = \beta_0 + \beta_1 x_{t1} + \ldots + \beta_k x_{tk} + \varepsilon_t, \quad (5)$$

"where $x_{t1} \ldots x_{tk}$ represent the values of the predictor variables for the t - tth observation, $\beta_0 \ldots \beta_k$ are coefficients estimated via OLS regression, ε_t is the error term, and γ_t is the response variable for the tth observation" (Valerdi, 2005). However, this technique makes the assumption that there is a lot of historical data, an assumption not fulfilled from the available 15 AMT historical cases (Griffiths, Carter Hill, & Judge, 1993). This number of historical cases is not sufficient to perform multiple regression on the full model containing 16 AMT drivers. Therefore, the model was tested and verified in a reduced form. To reduce the final Resources model, each of the drivers were clustered into the themes detailed earlier in the 'Resources Model Driver Study' subsection. These included: Development Team Factors (Table 4), Demonstration and Application Factors (Table 5), Project Factors (Table 6), and a Product Rate Factor (Table 7). The three size drivers were combined to form an overall size predictor and were compiled with the drivers clustered in the four themes. The reduced model's one size and four effort predictors are listed in Table 17, showing a logarithmic scale and summary description.

In order to express the required linear relationships, logarithmic transforms were applied to the dependant and independent variables of the reduced model and are presented in Equation (6):

$$\text{In}\,(\text{DEVELOPMENT\_PERSONHOURS}) = \beta_0 + \beta_1 \text{In}\,(S_1) + \ldots + \beta_5 \text{In}\,(\text{EM}_4)\,. \quad (6)$$

The reduced model's five parameters are presented in Equation (7):

$$\begin{aligned}\log\,(\text{DEVELOPMENT\_PERSONHOURS}) = {} & \log(\text{SIZE}) + \log\,(\text{TEAM}) \\ & + \log\,(\text{DEM}) + \log\,(\text{PROJECT}) \\ & + \log\,(\text{PRODUCT})\,.\end{aligned} \quad (7)$$

Reduction of the model predictors granted the following multiple regression diagnostic tests:

- **Model significance/*F*-test.** An F-test was performed on the Resources model to validate the significance of the reduced model hypothesis. The final F-value for the reduced Resources model is listed in Table 18, identifying exceptional statistical significance of the hypothesis.

TABLE 17 Reduced Resources model predictor descriptions

Predictor	Term	Description
S_1	Log (SIZE)	Functional Size Factors. Drivers that capture the functional size of the AMT.
EM_1	Log (TEAM)	Development Team Factors. Drivers that capture the skill set and comprehension of the development team.
EM_2	Log (DEM)	Demonstration and Application Factors. Drivers that capture the complexity of the process and its target application.
EM_3	Log (PROJECT)	Project Factors. Drivers that capture the project requirements.
EM_4	Log (PRODUCT)	Product Rate Factor. The driver that captures the required production rate of the assigned product.

TABLE 18 Reduced Resources model performance

Model name	Predictors	*R*-Squared	Observations	*F*-Value
COTECHMO Resources	5	0.98	15	106.65

TABLE 19 Reduced Resources model *t*-value and *p*-value

Model predictor	*t*-Value	*p*-Value
Size	13.877971	0.000000
Team	9.385357	0.000006
Demonstration and application	11.217564	0.000001
Project	5.799852	0.000260
Production rate	−1.848895	0.097522

- **Sensitivity Analysis.** Identification of the relevance of predictor data points within the reduced Resources model was performed and tested for statistical significance. *t*-Values and *p*-values were used to compare the influence of individual predictors on the mean function. "A *t*-value is the ratio between the estimate and its corresponding standard error, where standard error is the square root of variance. In general terms, the higher the *t*-value, the stronger the statistical significance of the predictor variable" (Valerdi, 2005). The reduced model's *t*-values had exceptional statistical significance for each of the model predictors listed in Table 19. However, the 'Production Rate' predictor did not have a high statistical significance. A *p*-value refers to the probability of observing a value, with outputs falling below 0.05, indicating high predictive influence on the mean function. Table 19 lists the final reduced model predictor *p*-values, with each meeting the specified value of 0.05, excluding the 'Production Rate' predictor. Enhancement of the 'Production Rate' predictor *t*-value and *p*-value is discussed in the conclusion with recommendations for future research. The reduced Resources model summary regression statistics for the 15 cases are listed in Table 18, identifying an exceptional *R*-squared value and an outstanding *F*-value, validating the model hypothesis.

Further to the multiple regression analysis, experts specified that each COTECHMO CER form must be verified using PRED (Prediction Level) values. For example, a PRED(20) value requires the forecast data to be within 20% of the actual (the historical value for the 15 AMT cases) (Conte et al., 1986). To calculate the PRED value for this application, the number of forecast cases falling within 20% of the actual data is divided by the total number of cases. For this case study, 8 of the 15 AMTs fell within 20% of the actual data, so 8 is divided by the total of 15, equating a value of 53%. Therefore, 53% of the data fell within PRED(20), 73% of the data fell within PRED(25), and 86% within PRED(30).

Direct Cost Model Verification

The COTECHMO Direct Cost model can be characterized by a multiple regression model. The model response is development direct cost and the predictors are the 14 drivers that have an influence on AMT Direct Cost. Following the format of the Resources model statistical verification discussed previously, the estimation of a linear application is predicted using the OLS approach. The multiple regression model is written in the form introduced previously in Equation (5). However, following the Resources model verification, the 15 AMT historical cases were not sufficient to perform multiple regression on the full model, including 14 AMT development drivers. Therefore, the Direct Cost model was also tested and verified in a reduced form. To reduce the Direct Cost model, drivers were clustered into the themes presented earlier in the 'Direct Cost Model Driver Study' subsection. These included: AMT Process Primary Factors (Table 10), AMT Process Secondary Factors (Table 11), AMT Process External Factors (Table 12), and a Product Rate Factor (Table 13). Each theme was compiled with the size driver and listed in Table 20, with a logarithmic scale and a summary description.

In order to express the required linear relationships, logarithmic transforms were applied to the dependant and independent variables, as presented in Equation (8):

$$\text{In(DEVELOPMENT\_DIRECTCOST)} = \beta_0 + \beta_1 \text{In}\,(S_1) + \ldots + \beta_5 \text{In}\,(\text{EM}_4)\,. \quad (8)$$

The Direct Cost model in its reduced form is presented in Equation (9):

$$\begin{aligned}\log(\text{DEVELOPMENT\_DIRECTCOST}) = \log(\text{SIZE}) &+ \log\,(\text{PRIMARY}) \\ &+ \log\,(\text{SECONDARY}) + \log\,(\text{EXTERNAL}) \\ &+ \log\,(\text{PRODUCT})\,.\end{aligned} \quad (9)$$

Reduction of the Direct Cost model granted the following multiple regression diagnostics to verify the model:

- **Model significance/*F*-test.** An *F*-test was performed on the Direct Cost model to validate the significance of the reduced model hypothesis. The final *F*-value for the reduced Direct Cost model is listed in Table 21, clarifying statistical significance of the hypothesis.

TABLE 20 Reduced Direct Cost model predictor descriptions

Predictor	Term	Description
S_1	Log (SIZE)	AMT Size Factor. The driver that captures the AMT process hardware size.
EM_1	Log (PRIMARY)	AMT Process Primary Factors. Drivers that capture primary process parameter requirements for the target application.
EM_2	Log (SECONDARY)	AMT Process Secondary Factors. Drivers that capture the secondary parameters of the process for the target application.
EM_3	Log (EXTERNAL)	AMT External Factors. Drivers that capture external AMT requirements for the target application.
EM_4	Log (PRODUCT)	Product Rate Factor. The driver that captures the required production rate of the assigned product.

TABLE 21 Reduced Direct Cost model performance

Model name	Predictors	R-Squared	Observations	F-Value
COTECHMO Direct Cost	5	0.76	15	5.59

TABLE 22 Reduced Direct Cost model t-value and p-value

Model predictor	t-Value	p-Value
Size	−4.420315	0.001670
Primary	−2.791522	0.021002
Secondary	−1.045489	0.323063
External	−3.625801	0.005522
Production rate	−1.285748	0.230626

- **Sensitivity Analysis.** Following the sensitivity analysis of the Resources model, identification of the relevance of predictor data points for the model were tested using t-values and p-values, listed in Table 22. The Size, Primary, and External predictors have outstanding t-values and p-values, both meeting the specified p-value of 0.05. However, Secondary and Production Rate predictors did not meet the specified p-value of 0.05, although each are discussed in the conclusion, with recommendations for future research. The summary regression statistics for the 15 cases are listed in Table 21, identifying a reasonable R-squared value and a significant F-value, validating the reduced model hypothesis.

Following the Resources model, experts specified that the CER form must be further verified using PRED values. The Direct Cost model's forecasting accuracy achieved 93% of the forecast data falling within PRED(20), 100% within PRED(25), and PRED(30).

Conclusion

At present, there are no existing cost models capable of forecasting aerospace AMT development person-hours and cost of hardware, at the initial stages of development. The research presented developed two novel parametric cost models. Each model was utilized to forecast development person-hours and direct cost of 15 AMTs, within a detailed case study. To verify and validate, multiple regression was performed on each model from the data generated within the case study. However, from the limited number of historical AMTs, each model's predictor parameters were clustered to form reduced models, enabling multiple regression evaluation.

The multiple regression analysis of the reduced COTECHMO Resources model identified a high R-squared and F-value, validating exceptional statistical significance of the hypothesis. Additionally, the model's clustered predictors had significant t-values with the aligned p-values, complying with the specified 0.05. However, the 'Production Rate' predictor had a low t-value combined with a p-value of 0.097, not meeting the specification limit. Despite these values not fulfilling the requirements, on detailed evaluation with Cost Estimation and AMT development experts, each predicted that the low variation was formed by the limited number of cases. Experts recommended this predictor for additional evaluation in future research, using a selection of further AMTs. If this analysis indicated a high p-value outside the specified 0.05, the predictor should be removed from the model.

The reduced COTECHMO Direct Cost model multiple regression presented a lower R-squared and F-value when compared to the Resources model. However, the F-value was sufficient to validate statistical significance of the hypothesis. Additionally, when performing a sensitivity analysis on predictor data points, three of the five predictors met the required p-value of 0.05. However, 'Secondary' and 'Production Rate' predictors did not conform and produced values of 0.32 and 0.23, respectively. The 'Secondary' predictor consisted of four drivers clustered into one predictor. To evaluate this high p-value, each of the drivers would need to be dissected and analyzed individually. This would require additional historical AMT cases, a subject of future research recommendations. Following the Resources model, evaluation of further AMTs would either validate or eliminate the 'Production Rate' predictor.

In summary, each model hypothesis has been proven using data from a leading aerospace manufacturing organization. However, future research should evaluate further AMTs to advance the verification and validation of each model. Furthermore, each model should be utilized outside the collaborating organization. This would further support each model hypothesis and extend the impact outside the supporting organization.

Acronyms

AMT	Advanced Manufacturing Technology
AP	Application Points
CER	Cost Estimating Relationship
CMR	Cost Multiplier Ratio
COTECHMO	Constructive Technology Development Cost Model
EMR	Effort Multiplier Ratio
FP	Function Points
MS	Microsoft
NASA	National Aeronautics and Space Administration
OLS	Ordinary Least Squares
PRED	Prediction Level
R&T	Research and Technology
SLOC	Software Lines of Code
TRL	Technology Readiness Level

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