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Abstract: The learning curve shows how unit costs can be expected to fall over time. It has been demonstrated that learning is a major cost risk driver in defence acquisition projects. It can be affected by changes in processes, resource availability, and worker interest. This paper examines the risk that military ship builders may not realise expected production efficiencies. A probabilistic risk approach is used to portray the learning curve risk and estimate the corresponding cost contingency. A case study using a military shipbuilding project is presented and discussed to illustrate the methodology.

Keywords: risk analysis; cost contingency; military; shipbuilding; learning curve.

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1 Introduction

In a time of tightening budgets, with operational requirements driving the need for accelerated acquisition schedules, defence leadership needs an early, independent, and agile approach for assessing risk of acquisition programs. Risk assessment is a fundamental process in project management. It provides a way to examine the impact of individual risks on the overall project objectives (e.g., cost, schedule) to determine the likelihood of finishing the project on budget (cost risk analysis) or on time (schedule risk analysis). Cost risk analysis allows program managers to estimate the requisite contingency reserve needed for a desired level of certainty about achieving the project cost plus reserve. Similarly, schedule risk analysis allows program managers to determine the schedule reserve required for a desired confidence level of the project completion time. These analyses can be conducted in the project's conceptual development phase as soon as there is a notional budget and schedule, and should be continued periodically throughout project execution as the estimate is refined and more risks are identified and quantified.

Typical risk areas related to defence acquisition programs may include logistics, management, funding, requirements, design, production, etc. Key risk factors that could affect the cost of an acquisition program may include foreign exchange, technology maturity, inflation, production rate, etc. In particular, it has been demonstrated that learning is a major cost risk factor that affects the production cost for defence acquisition projects. Indeed, it is often found that the resources required for making individual units decrease as production volumes increase. It costs more to produce the first unit (e.g., aircraft, ship) than it does to produce additional units. In part, this is due to the cost improvement or learning curve effect (i.e., a large quantity ordered over time will lead to accumulated experience in producing the same system year after year, reducing the unit cost) and the production rate effect (i.e., the quantity of units produced in a given time period with high production rates likely reducing the unit cost through greater operating efficiency and the spreading of fixed costs over more units). The learning curve effect is a human phenomenon that occurs because of the fact that people get quicker at performing repetitive tasks once they have been doing them for a while. The first time a new process is performed, the workers are unfamiliar with it since the process is untried. As the process is repeated, however, the workers become more familiar with it and better at performing it. This human performance can also be enhanced by more improved processes. Some authors have expanded the concept of learning to include redesign of the production process itself (Matthew et al., 2003). The learning curve is also known in the literature as the experience curve, the improvement curve, or the progress curve.

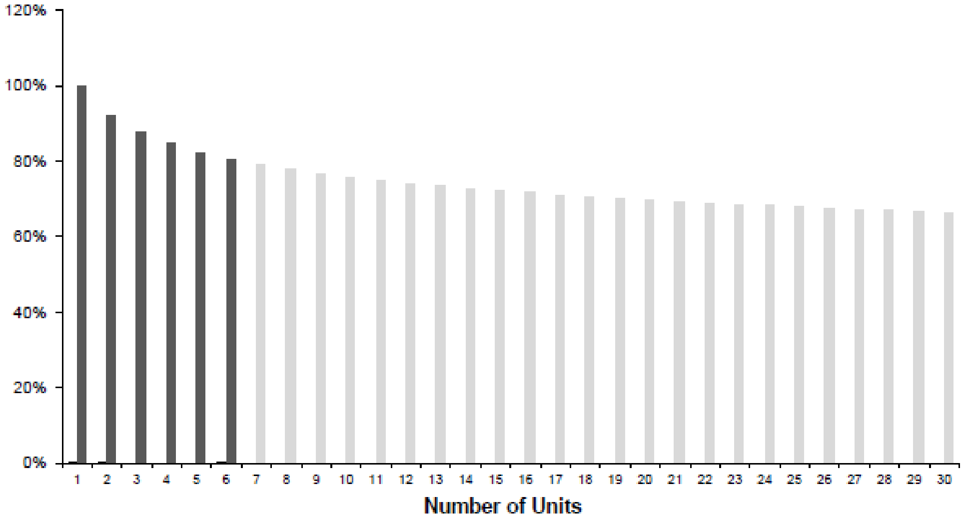
To illustrate this concept, Figure 1 presents an example of learning curve for international naval industry (Australian Submarine Corporation, 2015). It shows how unit costs can be expected to fall over time due to the efficiency gained by accumulated experience and the production rate economies of scale. It can be affected by changes in processes, resource availability, worker interest, etc. Naval industry is now focusing on high value added, low volume work. This situation significantly reduces order numbers for warships and submarines and limits the learning curve benefits.

Learning is the acquisition of knowledge or skill. This multilevel process can be divided into two components: Operational and conceptual learning. Operational learning is the acquisition of know-how whereas conceptual learning is the acquisition of know-why. One can also differentiate between two other levels of learning: explicit and implicit learning (Polanyi, 1968; Reber, 1993; Nonaka, 1994; Ichijo and Nonaka, 2007). While explicit learning can formally occur through letters, reports and databases, implicit or tacit learning is said to happen via dialogue and practice. Organisational knowledge theorists have also distinguished between individual and organisational learning. Individual learning takes place when knowledge is acquired (or created) and applied by individuals. It becomes organisational learning when individual knowledge is shared, combined, expanded, tested, and applied within the organisation. (Barker-Scott, 2011).

The culture of continuous professional development as represented by the Sino-Japanese word kaizen usually delivers small improvements. If these small improvements are aligned with more performing organisational total quality management (TQM), they can yield a large overall improvement in productivity (Deming, 1993; Colenso, 2000).

Note, however, that learning curve is not a measure of productivity in warship construction. Shipyard productivity is generally measured as a function of the gross number of man-hours required to build a ship, not the saving between ships in a series. Factors that affect shipyard productivity include the TQM, automation, geographic and physical constraints, numbers, skills and experience of the workforce as well as national industry structure (Defence SA Advisory Board, 2009).

Figure 1 The learning curve for naval production



Source: Australian Submarine Corporation (2015)

A learning curve is generally characterised by the learning rate at which the unit cost is reduced through learning and experience. Learning rates vary significantly across and within industries (Yelle, 1979; Dutton and Thomas 1984; Thompson, 2001). They range generally between 80% and 85% in the shipbuilding sector which means a reduction in cost between 15% and 20% with every doubling of production (Stewart and Wyskida, 1995). Military ship procurement is a major defence acquisition program. In the USA, for example, it represents approximately 10% of the Navy's budget. It typically involves a few individually expensive projects with an irregular schedule of new starts. Even with a long-range plan, such a situation may lead to major fluctuations in year-to-year budgets causing both a slip in project schedule and cost overruns (Blickstein and Smith, 2002).

This paper describes, mostly in a case study style, how learning as a major cost risk factor has been successfully analysed in defence acquisition projects. More specifically, it shows how a learning curve model can be used in a probabilistic risk assessment to provide a risk-adjusted cost estimate for a defence shipbuilding project. Risk in this methodology is defined as a measure of the potential variation in achieving the expected production efficiency. The paper indicates why a learning curve model is selected and how it can be adapted to the military shipbuilding sector. It also shows how the application of this technique has contributed to advancements in defence cost estimating.

The paper is organised into five sections. Following the introduction, Section 2 presents a comprehensive overview of the cost risk analysis methods for defence acquisition projects. Section 3 highlights the mathematical background of the used learning curve model and discusses the cost contingency estimation associated with the learning curve risk. Section 4 provides an illustrative example to portray the learning curve risk using a defence shipbuilding project. Concluding remarks and directions for future research are indicated in Section 5.

2 Cost risk analysis methods overview

A number of cost risk analysis methods for defence acquisition projects have been developed in the literature over the last five decades. They range from simple qualitative methods using subjective judgements and ordinal scaling techniques to more advanced quantitative methods using simulation and statistical models (Sokri and Ghanmi, 2015). Qualitative methods are quick and cost-effective methods for prioritising risks. They would be used at early stages of the project development to provide a high level assessment of cost risk when there is limited data (or the project requirements have not been established) but the project definition is good enough to make necessary adjustments. However, the analysis should be reviewed during the project's life cycle to stay current with changes in project risks. The process can lead to further analysis in planning quantitative risk analysis or directly to risk response. The main benefit of these methods is that they allow decision makers to reduce the level of uncertainty about the project and concentrate on high-priority risks (Arena et al., 2008; US Air Force, 2007; NASA, 2008; Hulett, 2012).

Quantitative methods provide the means to examine the impact of risks on the overall project cost and to estimate the requisite contingency reserve at later stages of the project development when sufficient data is available to conduct detailed risk analysis. Key quantitative cost risk analysis approaches include convolution, scenario-based and stochastic simulation methods.

2.1 Convolution

Convolution is the combination of independent random variables. It is usually used to derive closed-form solutions to statistical problems. The traditional way to represent cost risk is to place uncertainty on the estimate for each project element using probability distributions. The project elements' probability distributions are combined together to determine the total project cost uncertainty. Three main ways are used to combine the probability distributions of the individual project elements and to derive closed-form solutions: manipulation of integrals, moment generating functions, and characteristic functions. While convolution is an effective method for cost risk analysis, it has many limitations (Hulett, 2012):

1. can only derive closed-form solutions for simple summation-type models where uncertain values can be easily represented by specific probability distributions
2. assumes in advance a type of probability distribution for the total project cost estimate
3. requires observed data to estimate the underlying probability density functions.

2.2 Scenario-based method

The scenario-based method (SBM) was developed as an alternative to advanced statistical methods for generating measures of cost risk. SBM is a quantitative risk analysis method centred on articulating risk scenarios as the basis for determining the amount of cost risk reserve needed for a project (Garvey, 2008). A scenario is a sequence of events; an account or synopsis of a possible course of action or outcome expected from possible events. If these events occurred, risk scenarios would result in costs higher than the level planned or budgeted for the project. Examples of risk scenarios for the acquisition of military systems would include change of inflation rate, increase of exchange rate, slip in project's schedule, change in technology readiness, reduction in production volume, the sensitivity of the project to budget variations, the vulnerability of the project to foreign intelligence collection efforts, the abilities of the contractors to design, develop, manufacture, and support the system, etc. (Defense Acquisition University, 2006). The process of defining risk scenarios is a good practice as it builds the necessary rationale for traceable and defensible measures of cost risk.

While the scenario-based method is easy to implement and provides a stochastic measure of cost estimate, it has some limitations. In addition to its subjectivity, the method does not produce an S-curve for detailed cost risk analysis and is not useful in aggregating lower-level risks. A statistical version of the method has been proposed (Garvey et al., 2012) to address this limitation but the new version requires two statistical input parameters: the probability the point estimate cost will not be exceeded and the underlying coefficient of variation. Both parameters are judgmental values and may make the method relatively inaccurate. However, combined with historical data, this statistical version of the method could be useful.

2.3 Stochastic simulation

The stochastic simulation uses mathematical models and probability distributions to determine cost estimate confidence of a project. In contrast with the convolution and the SBM methods that determine cost estimate confidence, the stochastic simulation method provides a detailed quantitative analysis of this confidence. This technique is able to combine probability distributions in most circumstances. It involves simulating the project cost impacts of all possible outcomes that might occur within a sample space of defined events. There are two main stochastic simulation methods for cost risk analysis (Hulett, 2012): *Cost driver* and *risk driver* methods.

2.3.1 Cost driver method

The cost driver method uses the cost breakdown structure of a project and represents each cost line item by a probability distribution indicating the variability in the cost estimate. The overall project cost is determined by adding up all the project cost elements.

2.3.2 Risk driver method

Unlike the cost driver method that uses the cost breakdown structure of a project, the risk driver method uses the risk breakdown structure to perform cost risk analysis. The method starts with the risk register's prioritised risks (i.e., strategic risks that have been identified and assessed as having high probability and high impact on the project cost) and drives the elements' cost risk directly from the risk themselves. Each risk item in the risk register database has two important characteristics: the probability that the risk may occur and the risk impact range. The impact range of a risk is specified in multiplicative terms (i.e., cost elements are multiplied by non-dimensional factors representing the risk impact). As for the cost driver method, the risk driver method uses probability distribution functions to represent the uncertainty in the risk impact and Monte Carlo simulation to combine the probability distributions of the individual cost elements for determining the total project cost. Unlike the cost driver method, the risk driver method allows for:

1 Multi-activity assignment (i.e., a risk could be assigned to multiple cost elements).

2 Compounded impact (i.e., a cost element may have several risks).

3 Implicit correlation. As the risk driver method distinguishes the impact of individual risks, it captures all of the risks' impacts on all of the cost elements they affect. As such, cost elements become implicitly correlated as the simulation proceeds.

One of the key risk drivers for military shipbuilding is the learning effect (Sokri, 2015). Defences analysts have recently started to combine learning curve models and scientific advances in risk analysis. A growing body of literature has begun to recognise statistical methods for learning curves as approved methods for proactive decision making in project evaluation. Thompson (2007), for example, estimates the rate of organisational forgetting in a seminal case study of USA wartime ship production. The study explored alternative formulations for the learning curve and investigated the relationship between organisational forgetting and labour turnover. Arena et al. (2008) used a learning curve that combines cost improvement and production rate effects to explore the causes of fixed-wing aircraft cost escalation. The authors concluded that customer-driven variables, such as procurement rates have contributed substantially to cost escalation. Kaluzny (2011) used the quantity effect model to determine best-fit learning and production rate slopes and provide a secondary cost projection of future F-35A Joint Strike Fighter production lots. The author estimated the underlying risk to facilitate the selection of an appropriate level of confidence for contingency planning. More recently, Sokri (2015) used a probabilistic risk assessment to evaluate the risks associated with the production cost of the Canadian Arctic/Offshore Patrol Ships (AOPS) project. The author estimated the distribution of the labour cost and provided a risk-adjusted cost estimate for the project. For a comprehensive literature review on this topic, the interested reader is referred to (Sokri and Ghanmi, 2015).

This paper uses a hybrid method combining a learning curve model with a simulation framework to provide a probabilistic risk assessment for a defence shipbuilding project. The learning curve model provides the unit cost improvement slope. The main output of the stochastic simulation methods is a probability distribution of the project cost estimate (and an S-curve). The S-curve can be used by decision makers in their risk analysis of defence acquisition projects. It is used in this paper to define a contingency for labour cost risk and to perform sensitivity analysis.

3 Learning curve model

This section discusses the learning curve model and presents its mathematical formulation. It also describes how a cost risk profile can be derived and how cost contingency can be determined.

3.1 Learning curve

In addition to the cumulative number of units produced, the conventional learning curve is occasionally augmented to include the rate of production in the current period. To present the principle underlying the augmented learning curve in military sector, let Q_i denote the midpoint of the i^{th} lot and LAC_i the lot average cost. The lot midpoint is the unit whose marginal cost is equal to the lot average cost (Matthew et al., 2003). The augmented learning curve model can be expressed as (Younossi et al., 2007):

$$LAC_i = T_1 \times \left[\bar{Q}_i(b) \right]^b \times r_i^c, \tag{1}$$

where r_i is the production rate of lot i. T_1, b, and c are parameters to be estimated. T_1 represents the cost of the first unit, b is the learning (or improvement) index and c is the production (or procurement) index. The lot midpoint $\bar{Q}_i(b)$ is expressed as a function of the learning index because it cannot be calculated without an estimate of this parameter. This model simultaneously explores the effects of learning and production. Learning will decrease the unit cost by reducing the corresponding required effort. The production rate may have positive or negative effects on unit cost. An increase in the rate of production may increase unit cost by increasing

1 the short-run price of materials
2 overtime labour costs
3 the failure rate of manufacturing equipment.

It can also reduce the average unit cost by spreading fixed costs over more units.

This two-factor learning curve has been used by many defence analysts to estimate the cost of military systems. For example, Arena et al. (2008) used the learning curve model (also known as the quantity effect model) to examine the cost improvement and production rate effects for 24 US military aircraft programs. The authors used in their analysis a diverse array of Air Force and Navy programs over 50 years, including attack, cargo, electronic, patrol, etc. However, there is a methodological limitation to this model that should be acknowledged: Cumulative quantity and production rate (measured by lot size as a proxy) may be positively correlated. This correlation may be observed when production runs are relatively short and can affect the accuracy and robustness of the estimates derived. Due to this restriction, Arena et al. (2008), for example, reduced the number of systems that could be analysed from 52 to 24.

In the military shipbuilding sector, ships are often purchased as individual units not as lots and cost data are presented rather by unit (Sokri, 2015). In this case, the production rate r_i is equal to one, the lot midpoint $\bar{Q}_i(b)$ is equivalent to the sequence number of the n^{th} ship in the production run, the lot average cost LAC_i is replaced by the marginal cost (or time) required to produce the n^{th} ship (C_n), and the model becomes the same as Wright's model (1936). Mathematically, the marginal cost (or time) required to complete the n^{th} ship is given by:

$$C_n = T_1 n^b, \tag{2}$$

and the regression analysis is then conducted on individual units rather than on the lot midpoints.

3.2 Learning rate estimation

By taking the logarithms on both sides, equation (2) can be rewritten as follows:

$$\ln\left(C_n\right) = \ln\left(T_1\right) + b \times \ln(n) \tag{3}$$

The two parameters $T_1$and b of this log-linear model can be estimated by applying an ordinary least squares (OLS) regression to equation (3) with an error term (Anzanello and Fogliatto, 2011). The dependent variable is $\ln(C_n)$ and the independent variable is $\ln(n)$. Wright's model assumes that as the quantity of units produced doubles, the time (or cost) it takes to produce an individual unit decreases at a constant rate u, mathematically, this effect can be stated as:

$$C_{2n} = C_n \times u \tag{4}$$

The uniform rate u in equation (4) is known as the unit cost improvement slope or the learning rate. This rate can be expressed as:

$$u = 2^b \tag{5}$$

The learning rate is the ratio of marginal costs between unit $2n$ and unit n. It may plausibly range from 0.5 (or 50%) to 1 or (100%). The lower the learning rate the higher the effects from learning. A learning rate of 85%, for example, implies that unit $2n$ costs only 85% as much to produce as unit n.

3.3 Cost risk profile and contingency

The cost risk profile can be derived and presented using the cumulative distribution function (CDF) of the incremental cost risk. More commonly known as an S-curve in quantitative cost risk analysis, this curve shows the likelihood of not exceeding a given cost. In this model, changes in the learning curve are compared to ship 1, referred to as the baseline scenario. We assume that there is no benefit from learning associated with this first ship.

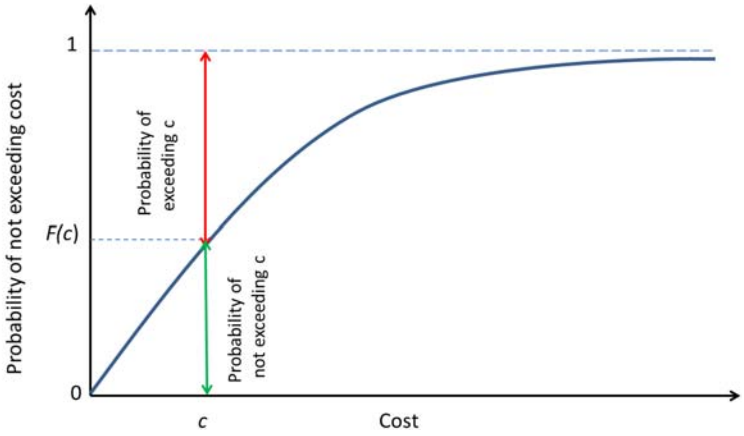
To present the concept of cost risk profile, let the incremental cost C be a random variable and F its CDF. As indicated in Figure 2, for each cost c, $F(c)$ represents the probability of achieving a cost less than or equal to c (assuming that F is continuous and strictly increasing).

$$F(c) = P(C \leq c). \tag{6}$$

By assumption, for each probability p ($0 \leq p \leq 1$), there is a unique real number c such that $p = F(c)$. The inverse function F^{-1} is the quantile function and $c = F^{-1}(p)$ is the $100p^{th}$ percentile. As F is continuous, the median is also the 50th percentile that is F^{-1} (0.5).

As F is strictly increasing, when the percentile value is low, the probability of exceeding the cost is high. In this situation the cost contingency is subsequently low (US Air Force, 2007; Sokri and Solomon, 2013). Contingency is a financial reserve set aside to offset potential cost increases due to future known or unknown events. Contingency is calculated as an incremental cost above the base estimate to reduce the risk of any cost overrun (Mak et al., 1998; Rad, 2002; AACE, 2009; Sokri and Solomon, 2014). This provision of money is necessary for providing a risk-adjusted cost estimate.

Figure 2 Cost risk cumulative distribution (see online version for colours)



4 Illustrative example

Many cost risk factors are generally identified in defence acquisition projects. Examples of these factors include foreign exchange, inflation, project's schedule, technology readiness, and production efficiency. Production efficiency (or learning curve) in the military shipbuilding sector is the risk that ship builders may not realise the expected production efficiency. In this paper, the learning curve model is applied to a shipbuilding project for the Canadian Armed Forces to examine the production efficiency risk and to estimate its labour cost contingency. However, to avoid issues with classified information, illustrative data is used in the scenario for discussion purposes.

4.1 Input data

The dataset contains records on the acquisition of five armed ships. Table 1 provides the number of hours required for each ship to be produced and the corresponding labour cost. In the Table, all costs are net of taxes and expressed in Canadian dollars. It takes, for example, more than 500,000 hours to produce the first ship and less than 400,000 hours to produce each of the two last ships. The ship production time and cost are decreasing, showing a learning curve effect. This effect states that time per ship produced decreases as the number of ships increases.

Table 1 Unit production time and cost

Ships	*Labour*	
	Hours	*Cost ($000)*
1	550,500	16,515
2	450,500	15,515
3	400,500	12,015
4	370,500	11,115
5	341,000	10,230
Total	*2,113,000*	*63,390*

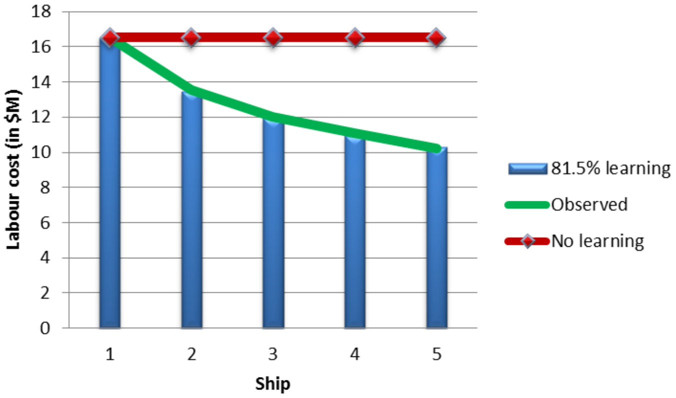
4.2 Learning rate

Applying OLS regression to equation (3) with an error term leads to the following log-linear function:

$$\ln\left(C_n\right) = 13.222 - 0.295 \times \ln(n). \tag{7}$$

In equation (7) the variable C_n denotes the marginal time required to produce the n^{th} ship. The number 13.222 is the logarithm of the time taken to produce the initial ship and –0.295 is the slope of the learning curve. This result means that as n increases, the time (or cost) required to produce the n^{th} ship C_n decreases. The learning rate that portrays the learning effect on each redoubling of the units would be $u = 2^{-0.295}$ or approximately 81.5%, which is within the range of the expected learning rates for shipbuilding projects (i.e., between 80% and 85%) as stated by Matthew et al. (2003). Figure 3 states that, as the number of ships produced doubles, the time (and consequently the labour cost) it takes to produce an individual ship reduce by about 18.5%. More specifically, the second ship would take 81.5% of the time of the first one and the fourth ship would take 81.5% of the time of the second one.

Figure 3 Effects of the learning rate on the unit direct labour cost (see online version for colours)

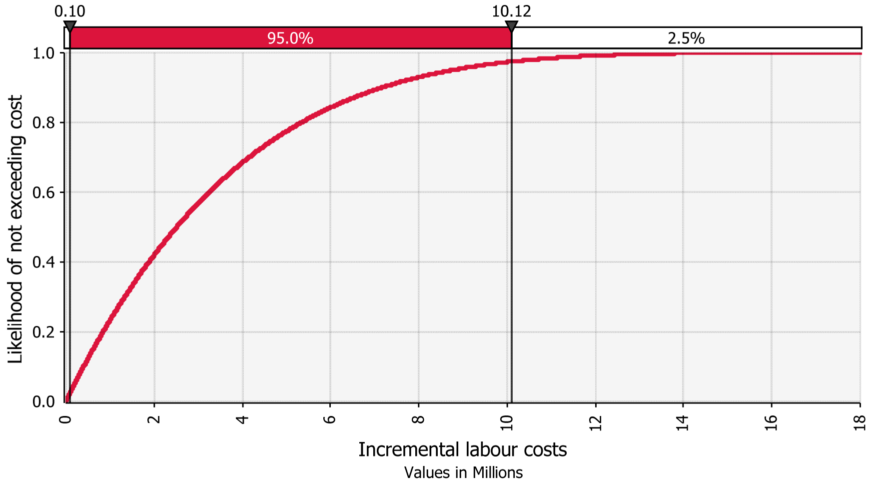


4.3 Cost contingency

Contingency is an important factor in project risk-adjusted cost estimate. If it is too high, the project may become ineffective and can be cancelled. Lower contingency may cause higher cost overrun. The next step in the analysis is to derive the labour cost profile and determine the cost contingency for each ship. The labour cost risk profile was determined using the learning curve model and a stochastic simulation method. A program evaluation and review technique (PERT) distribution was also used to represent the most likely incremental costs and the corresponding probable spread. This distribution has a number of desirable properties. Like the Triangular distribution, PERT is used as a modelling tool where the high and low thresholds and the most likely value are known. It is, however, more adequate than the Triangular distribution when the distribution is skewed. Figure 4 shows the range of possible total amounts of the risk contingency and their relative likelihood of occurrence. The 95% confidence interval for this contingency would range from $0.10M to $10.12M. Labour cost contingency is derived from the quantile function. The level of confidence should correspond to the decision maker's risk tolerance. Up to now, no confidence level is considered as optimal for defence acquisition projects (United States Government Accountability Office, 2009), but it is common to analyse projects between 50% and 80% levels (Treasury Board Secretariat, 2012).

Table 2 summarises the main percentiles (incremental labour costs) and the corresponding likelihood of not exceeding this cost by ship. In the table, changes in the learning curve are compared to ship 1. For ship 2, the amount of the risk contingency would be approximately $0.39M, using the median (50th percentile). If the budget is set at the 80th percentile, this amount would become approximately $0.84M. The total amount of the risk contingency (all ships) would be approximately $2.5M, using the median and $5.3M if the budget is set at the 80th percentile. In this analysis, contingency is seen as a financial treatment for the learning curve risk. Added to the budget estimate, it establishes the total financial commitment for the project. It should normally be used in conjunction with other risk mitigation strategies (Baccarini, 2004).

Figure 4 Distribution of cost risks (see online version for colours)



In real-world applications, this technique and the corresponding results can help decision makers to estimate the requisite contingency reserve for production cost risk. It can also be used to conduct sensitivity analysis and generate early and independent secondary cost projections. Attention should, however, be drawn to other issues when analysing the learning curve risk. The estimated learning rate implicitly depends on assumptions made about the knowledge depreciation trend and its steady state. Knowledge loss may lead to reversals in production efficiencies causing increases in production costs. Knowledge loss may be attributed to many factors such as time, interruptions to production, labour turnover, individual forgetting, organisational forgetting, and technological change (Thompson, 2007). In the naval industry, important productivity gains have been achieved from learning over the past decades; further gains would come from other factors in the future. These factors include more efficient organisation, improved processes, and technical innovation (Australian Submarine Corporation, 2015). They could offer not only a less costly and more efficient processes, but also stronger mitigation strategies such as continuous professional development and more performing organisational memory system.

Table 2 Percentiles for the incremental labour costs

Likelihood (%)	*Expected labour cost contingency ($)*				
	Ship 2	*Ship 3*	*Ship 4*	*Ship 5*	*Total*
50	394,793	591,013	716,683	807,094	2,509,584
55	450,160	673,889	817,175	920,261	2,861,486
60	510,681	764,483	927,061	1,043,998	3,246,223
65	577,590	864,668	1,048,525	1,180,776	3,671,558
70	652,649	977,023	1,184,769	1,334,213	4,148,654
75	738,491	1,105,525	1,340,588	1,509,692	4,694,296
80	839,366	1,256,541	1,523,724	1,715,935	5,335,566

5 Conclusions

The learning-by-doing theory assumes that a learning process will take place as task repetition occurs. This learning effect may occur in the military shipbuilding sector only if the cumulative experience allows ship builders to decrease their building time and cost. The objective of this paper was to examine the learning curve risk associated with military shipbuilding projects and to estimate the corresponding cost contingency.

The paper indicated for what purpose a learning curve model could be used and how it could be adapted to the military shipbuilding sector. It also showed how the model could be combined with a stochastic simulation method to estimate labour cost contingency. Some strategic initiatives where the method has had a significant influence were also mentioned. Further efforts are ongoing to address other aspects of the learning curve risk. Examples of such challenges include (but are not limited to) the determination of the steady state where knowledge level and unit cost remain constant over time as well as the description of concrete risk mitigation strategies to prevent risk events from happening.

References

Anzanello, M.J. and Fogliatto, F.S. (2011) 'Learning curve models and applications: literature review and research directions', *International Journal of Industrial Ergonomics*, Vol. 41, No. 5, pp.573–583.

Arena, M.V., Younossi, O., Brancato, K., Blickstein, I. and Grammich, C.A. (2008) *Why Has the Cost of Fixed-Wing Aircraft Risen? A Macroscopic Examination of the Trends in US Military Aircraft Costs over the Past Several Decades*, RAND Corporation Report MG-696-NAVY/AF, CA, USA.

Association for the Advancement of Cost Engineering (AACE) International (2009) *Risk Analysis and Contingency Determination Using Expected Value Association for the Advancement of Cost Engineering International*, Recommended Practice No 44R-08.

Australian Submarine Corporation (2015) *A Sustainable Australian Naval Industry* [online] available: https://www.asc.com.au (accessed 5 October 2015).

Baccarini, D. (2004) 'Estimating project cost contingency – a model and exploration of research questions', in F. Khosrowshahi (Ed.): *20th Annual Association of Researchers in Construction Management (ARCOM) Conference*, Edinburgh, UK, September.

Barker-Scott, B. (2011) *Organizational Learning: A Literature Review*, Discussion paper no. 2011-02, Queen's University IRC.

Blickstein, I and Smith, G. (2002) *A Preliminary Analysis of Advance Appropriations as a Budgeting Method for Navy Ship Procurements*, RAND Corporation Report MR-1527, CA, USA.

Colenso, M. (2000) *Kaizen Strategies for Improving Team Performance*, Pearson Education Limited, London.

Defence SA Advisory Board (2009) *The Naval Shipbuilding: Australia's $250 billion Nation Building Opportunity*, Discussion paper.

Defense Acquisition University (2006) *Risk Management Guide for DoD Acquisition*, 6th ed., US Department of Defense.

Deming, E.W. (1993) *The New Economics for Industry, Government, and Education*, MIT Press, Boston, MA.

Dutton, J.M. and Thomas, A. (1984) 'Treating progress functions as a managerial opportunity', *Academy of Management Review*, Vol. 9, No. 2, pp.235–247.

Garvey, P.R. (2008) 'A scenario-based method for cost risk analysis', *Journal of Cost Analysis and Parametrics*, Vol. 1, No. 1, pp.65–76.

Garvey, P.R., Flynn, B., Braxton, P. and Lee, R. (2012) 'Enhanced scenario-based method for cost risk analysis: theory, application, and implementation', *Journal of Cost Analysis and Parametrics*, Vol. 5, No. 2, pp.98–142.

Hulett, D. (2012) *Integrated Cost-Schedule Risk Analysis*, Gower Publishing, Farnham, UK.

Ichijo, K. and Nonaka, I. (2007) *Knowledge Creation and Management,* Oxford University Press, Oxford.

Kaluzny, B. (2011) *The Unit Recurring Flyaway Cost of a Canadian Joint Strike Fighter*, DRDC CORA TM 2011–200, Ottawa, Canada.

Mak S., Wong, J. and Picken, D. (1998) 'The effect on contingency allowance of using risk analysis in capital cost estimating a Hong Kong case study', *Construction Management and Economics*, Vol. 16, No. 6, pp.615–619.

Matthew, S., Goldberg, M.S. and Touw, A. (2003) *Statistical Methods for Learning Curves and Cost Analysis*m, The CNA Corporation, Virginia, USA.

NASA (2008) *Cost Estimating Handbook*, NASA Cost Analysis Division, Washington, DC, USA.

Nonaka, I. (1994) 'A dynamic theory of organisational knowledge creation', *Organisation Science*, Vol. 5, No. 1, pp.14–37.

Polanyi, M. (1968) *The Tacit Dimension*, Routledge, London.

Rad P.F. (2002) *Project Estimating and cost Management*, Management Concepts, Vienna¸VA, USA.

Reber, A.S. (1993) *Implicit Learning and Tacit Knowledge: An Essay on the Cognitive Unconscious*, Clarendon Press and Oxford University Press, New York and Oxford.

Sokri, A. (2015) *Arctic/Offshore Patrol Ship (AOPS) DRDC-RDDC-2015-L224*, July.

Sokri, A. and Ghanmi, A. (2015) 'Cost risk analysis methods for defence acquisition projects', *Proceedings of the International Conference on Risk Analysis ICRA 6/RISK 2015*, Barcelona, 26–29 May 2015, Fundación MAPFRE, Madrid, Spain.

Sokri, A. and Solomon, B. (2013) *Cost Risk Analysis and Contingency for the NGFC DRDC CORA TM 2013-224,* DRDC, Ottawa, Canada.

Sokri, A. and Solomon, B. (2014) *Risk Analysis and Contingency for the Next Generation Fighter Capability – Edition 2014.* DRDC-RDDC-2014-L289, DRDC, Ottawa, Canada.

Stewart, R.D. and Wyskida, R.M. (1995) *Cost Estimator's Reference Manual*, 2nd ed., Wiley Interscience, USA, New York.

Thompson, P. (2001) 'How much did the liberty shipbuilders learn? New evidence for an old case study', *Journal of Political Economy*, Vol. 109, No. 1, pp.103–137.

Thompson, P. (2007) 'How much did the liberty shipbuilders forget?', *Management Science*, Vol. 53, No. 6, pp.908–918.

Treasury Board Secretariat (2012) *Next Generation Fighter Capability: Life Cycle Cost Framework*, Treasury Board Secretariat, Ottawa, Canada.

United States Government Accountability Office (2009) *GAO Cost Estimation and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*, GAO-09-3SP, Washington, D.C., USA.

US Air Force (2007) *Cost Risk and Uncertainty Analysis Handbook*, ESC/XPK, Maryland, USA.

Wright, T.P. (1936) 'Factors affecting the cost of airplanes', *Journal of the Aeronautical Sciences (Institute of the Aeronautical Sciences)*, Vol. 3, No. 4, pp.122–128.

Yelle, L.E. (1979) 'The learning curve: historical review and comprehensive survey', *Decision Science*, Vol. 10, No. 2, pp.302–328.

Younossi, O., Arena, M.V., Brancato, K., Graser, J.C., Goldsmith, B.W., Lorell, M.A., Timson, F. and Sollinger, J.M. (2007) *F-22A Multiyear Procurement Program: An Assessment of Cost Savings*, RAND Corporation Report MG-664-OSD, CA, USA.

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The learning curve shows how unit costs can be expected to fall over time. It has been demonstrated that learning is a major cost risk driver in defence acquisition projects. It can be affected by changes in processes, resource availability, and worker interest. This paper examines the risk that military ship builders may not realise expected production efficiencies. A probabilistic risk approach is used to portray the learning curve risk and estimate the corresponding cost contingency. A case study using a military shipbuilding project is presented and discussed to illustrate the methodology.

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