Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 47 (2016) 84 – 89

www.elsevier.com/locate/procedia

Product-Service Systems across Life Cycle

Towards a Cost Engineering Method for Product-Service Systems based on a System Cost Uncertainty Analysis

Arturo Estrada[1] and David Romero[1-2*]

[1]Tecnológico de Monterrey, Del Puente 222, Col. Ejidos de Huipulco, Tlalpan, Mexico, 14380
[2]Griffith University, 170 Kessels Rd, Nathan QLD 4111, Australia
* Corresponding author. Tel.: +52 (55) 5483-1605; Fax: +52 (55) 5483-1606. E-mail address: arturoestrod@hotmail.com, david.romero.diaz@gmail.com

Abstract

The following research work introduces a Cost Engineering Method for Product-Service Systems (PSS) based on a System Cost Uncertainty Analysis (SCUA). The proposed SCUA is a probabilistic method focused on determining the total operational cost of a PSS. The main purpose of this paper is to introduce a PSS cost engineering approach that reduces the aleatory uncertainty that exists in every PSS cost determination, and therefore provides certainty in the cost-capacity relationship that exists in every PSS offering.

Keywords: Product-Service Systems; Cost-Engineering; Holistic Costing; System Cost Uncertainty Analysis.

1. Introduction

Original Equipment Manufacturers (OEMs) have become increasingly interested in understanding and managing the cost of their commitments (e.g. performance- and availability-based contracts) to deliver specific Product-Service System (PSS) results to their customers through-life [1]. However, current PSS costing approaches in literature hardly offer a real holistic approach for PSS cost engineering, considering the system of systems nature of a PSS. A PSS can be then defined as: *"a system of systems consisting of a system product and a set of system services, which are jointly capable of fulfilling a specific customer demand"*.

Based on previous research [1] [2], this paper proposes a probabilistic method to determine the total operational cost of a PSS, based on a System Cost Uncertainty Analysis (SCUA), which aims to capture the *aleatory uncertainty* that exists in every cost determination. The main difference from other cost engineering approaches is that the present work proposes to treat *functional performance* as a random variable. This enables us to consider that the cost behavior of a PSS is influenced by the interconnections/interactions among its subsystems (resulting in a holistic approach).

A comprehensive a literature [3], identified the need for holistic PSS cost engineering approaches. Current trends for PSS cost estimation are based on four main approaches [3]: (a) cost estimation by analogy, (b) activity-based costing, (c) parametric method, and (d) extrapolation. The selection of a PSS cost estimation method largely depends on the available data, and more than one method is normally applied in order to reduce *uncertainty* in the cost prediction, but the most popular method is *estimation*. It is proposed then that a change from *cost estimation* to real *cost engineering* must be made in order to reduce *uncertainty* in PSS costing.

It is important to mention that the proposed cost engineering method for PSS, includes a PSS Ontology, based on System Quality Attributes (SQA) [see 2], in order to initially measure the functionality of the PSS, from which total operational cost will be calculated. The main purpose of the *PSS-SQA Ontology* is to reduce the *epistemic uncertainty* involved in the behavior description of a PSS. Since the main objective of this research is to provide *certainty* in the *cost-capacity relationship* that exists in every PSS offering, both the research *method* and *ontology* [2] are intended to mitigate the entire spectrum of *uncertainty* (aleatory and epistemic).

doi:10.1016/j.procir.2016.03.216

2. Product-Service System (PSS) Functionality

According to literature [4], the focus of a PSS is on the delivery of functions. It is widely accepted that PSS constitute a paradigm shift from selling pure products or pure services to an integrated value offering, where the customer looks for functionality instead of ownership [5], where a *function* is defined as: *"the intended purpose of the system"* [6].

In order to understand how well a PSS's function has to be performed, the concepts of *functional result* and *functional performance* are introduced. The *PSS functional result* is defined as a standardized unit of function delivery (system output), while the *PSS functional performance* expresses the quality and quantity of functional results [4]. The relationship between *functional result* and *functional performance* is shown in Fig. 1 and Fig. 2.

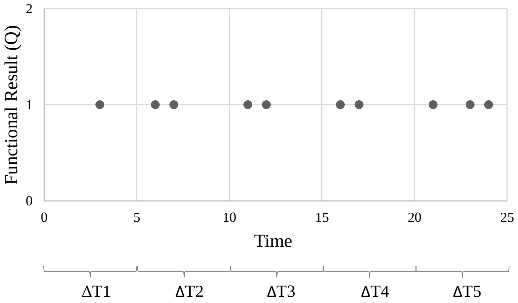

Fig. 1. Functional Results Delivery (Q)

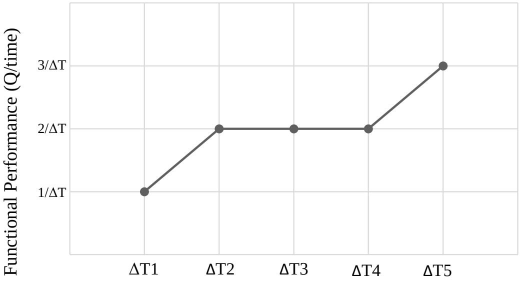

Fig. 2. Functional Performance (Q/Time)

Both *functional result* and *functional performance* must be defined in the design stage of a PSS lifecycle by the PSS engineering team, which will be the responsible for the cost and functionality aspects of a PSS development.

3. System Cost Engineering

Cost Engineering is defined as: *"the area of engineering practice where engineering judgment and experience are used in the application of scientific principles and techniques to problems of cost estimating, cost control, business planning and management science, profitability analysis, project management, and planning and scheduling"* [7].

The proposed PSS cost engineering method focuses on the *cost estimation* problem of the above definition. *Cost Engineering* can be then simply defined as: *"a methodology used for predicting/forecasting/estimating the cost of a work activity or output"* [8]. Every cost prediction entails a certain amount of *uncertainty.*

3.1. Uncertainty Theory

Uncertainty is defined as: *"any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system"* [9], and can be classified as *Epistemic* or *Aleatory*. *Epistemic uncertainty* arises from the limits of the human knowledge (e.g. events regarding the future: obsolescence, changes in legislations, etc.), its influence can be reduced through increased understanding and/or increased availability of relevant data. *Aleatory uncertainty* arises from the random nature of the analyzed entity, where independently of the available data events remain unpredictable [10].

The current trend in the PSS cost estimation field regarding *uncertainty* is divided into two types: (a) probability theory, and (b) evidence theory, interval analysis, and possibility theory [10]. The second classification is focused on issues that arise from data: vagueness, lack of data, and lack of structure. It can be seen that *probability theory* works with *aleatory uncertainty,* while the *compounding theories* of the second classification work with *epistemic uncertainty.*

3.2. Ontology and Epistemology Relationship

Ontology describes the form and nature of reality to be studied, while *Epistemology* is the way to understand the world and communicate this knowledge [11]. The two are related since *ontology* defines the cognitive boundaries of the piece of reality described, which represents the constraint of what can be known from this piece of reality. An ontology is used in order to organize information and reduce complexity. Therefore, it is stated that *epistemic uncertainty* is a matter of perspective because…*"The way we look at phenomena not only influences but determines what we are able to see and in the end determines what we are able to find"* [12].

Among several ontologies that describe the same piece of reality, some may entail a higher complexity for the determination of relevant data. In [2] a *PSS-SQA Ontology* was introduced to describe the complex nature of a PSS as a system of systems, and to reduce *epistemic uncertainty,* in particular knowledge about *functional performance*.

The scope of the proposed cost engineering method is focused on the total operational cost of a PSS calculated using complex probabilistic models and Monte Carlo simulation.

The probabilistic approach is not only supported by the *PSS-SQA Ontology* [2], but we believe that it will be able to reduce the *epistemic uncertainty* of analyzed events, and cost estimation will be based on these methods.

3.3. Systems Cost Uncertainty Analysis

Systems Engineering as a discipline compounds the required scientific and engineering efforts in order to develop, produce and sustain systems [13]. The cost estimation of any future system is one of the key aspects to attain a successful design. The PSS engineering team should carry out a *Cost Uncertainty Analysis* in which the costs impacts of uncertainties associated with a system's technical definition and cost estimation methods are quantified [13] [14].

Systems Cost Uncertainty Analysis (SCUA) defines three types of uncertainties: (a) cost estimation, (b) requirements, and (c) system definition [14]. *Cost estimation uncertainty* originates from the inaccuracy of the cost estimation models due to the misuse (or lack) of cost data, or from misapplied cost estimation methods, and it is also affected by economic changes. *Requirements uncertainty* originates from changes in the definition of the system's purpose. And, *system definition uncertainty* originates from the possible system configurations, which may be expressed as the *equifinality* property that all systems present.

The proposed *PSS-SQA Ontology* [2] (see Fig. 2) is intended to mitigate the effects that *system definition uncertainty* and *requirements uncertainty* exert on the *Total PSS Operational Cost determination.* The *PSS-SQA Ontology* aims to measure the functionality of a PSS by means of the use of System Quality Attributes (SQA) [2] and provides insights about: (a) what a PSS can do (capability)?, and (b) how well does a PSS perform (performance capacity)? Both, the *PSS-SQA Ontology* [2] (see Fig. 3) and the following PSS cost engineering method (see Fig. 4 and Fig. 5) aim to provide *certainty* in the *cost-capacity relationship* of a PSS offering.

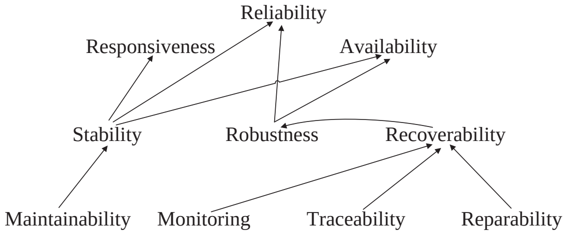

Fig. 3. PSS-SQA Ontology [2]

The relationship between the *PSS-SQA Ontology* [2] and the following PSS cost engineering method is depicted in Fig. 4.

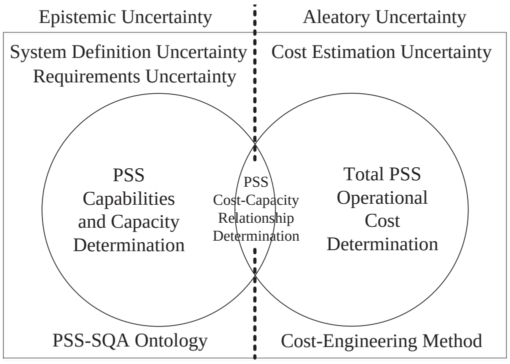

Fig. 4. PSS-SQA Ontology and PSS Cost Engineering Method Relationship

4. A Probabilistic Method of PSS Cost Engineering

It is proposed to create a *total cost probability model* in order to capture the *PSS cost estimation uncertainty*. This model provides *probability-based assessments* for the *Total PSS Operational Cost* for a particular PSS configuration and a particular PSS purpose; when the PSS purpose or configuration is changed, a new *total cost probability model* is likely to be developed.

The *Total PSS Operational Cost* is an uncertain quantity, which implies that a range of possible costs exists…*"The mathematical vehicle for working with a range of possible costs is the probability distribution, with cost itself viewed as a random variable"* [13]. More precisely it is considered as a *continuous random variable;* a random variable is continuous if its set of possible values is uncountable. This does not imply that the cost is random, but rather that it is composed by a great amount of very small compounding elements, whose individual contributions are not able to be defined in a degree of detail sufficient to calculate the total cost precisely [13]. It is rather a matter of efficiency, tackled as a random statistical process (stochastic process). The proposed *PSS Cost Engineering Probabilistic Method* is depicted in Fig. 5.

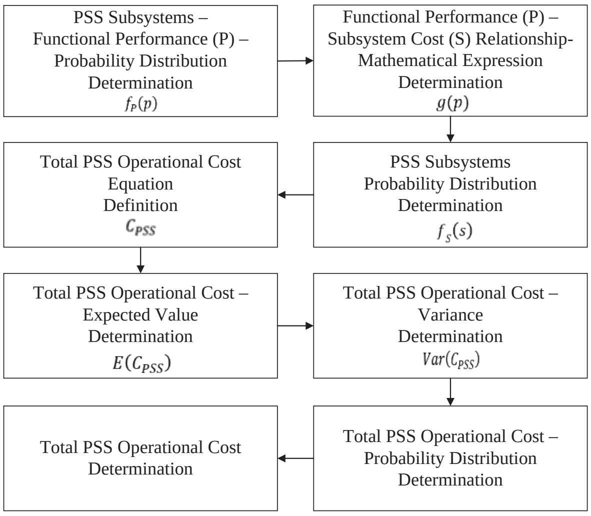

Fig. 5. Proposed PSS Cost Engineering Probabilistic Method

4.1. Costs Probability Models of Subsystems

The individual cost of every PSS subsystem is considered as a random variable $\boldsymbol{S_i}$. Every $\boldsymbol{S_i}$ random variable is defined to be a function of the random variable *functional performance* (P) of the PSS subsystem:

$$\boldsymbol{S_i} = \boldsymbol{g}(\boldsymbol{P_i}) \tag{1}$$

Where $\boldsymbol{g}(\boldsymbol{P_i})$ represents how the cost is related to the *functional performance* of the PSS subsystem. This representation completely depends on the analyzed PSS subsystem behavior. Since functional performance is considered as a random variable, it is necessary to define its probability density function $\boldsymbol{f_P}(\boldsymbol{p})$ in order to capture its *uncertainty*. From *Systems Cost Uncertainty Analysis (SCUA)* several density functions have proven to be useful, the most common ones are [13]: trapezoidal, triangular, uniform, Beta, Normal, and Lognormal. The task of the PSS engineering team at this step is to define both $\boldsymbol{g}(\boldsymbol{p})$ and $\boldsymbol{f_P}(\boldsymbol{p})$. According to [13] in the lack of historical data, distributions of random variables must often be specified by expert technical opinion. Therefore, it is a matter of subjective probability, in which a 'degree of belief' is measured…*"Subjective probabilities are most often associated with one-time, non-repeatable events,* *those whose probabilities cannot be objectively determined from a population of outcomes developed by repeated trials, observations or experimentation"* [13]. Hence, the probability distributions for the *functional performance* random variables are specified directly or are generated.

As stated in Equation 1, the cost of a PSS subsystem depends on its *functional performance behavior.* Therefore, a random variable transformation must be carried out in order to obtain the PSS subsystem cost probability density function $\boldsymbol{f_S(s)}$.

4.2. System of Systems Cost Probability Model

Once every PSS subsystem cost uncertainty is captured, it is possible to define the *PSS System of Systems (SoS) Cost behavior.* This behavior is represented in the random variable *Total PSS Operational Cost* (C_{PSS}), expressed as:

$$\boldsymbol{C_{PSS} = S_1 + S_2 + S_3 + S_4 + \cdots + S_n} \quad (2)$$

$\boldsymbol{C_{PSS}}$ an uncertain quantity with a range of possible values. A useful value to determine is its *expectation* $\boldsymbol{E(C_{PSS})}$ (i.e., the mean), which is the sum of all its possible values weighted by the probabilities associated with these values [15]. According to the *Strong Law of Large Numbers*, for sufficiently large number of experiment repetitions, it is virtually certain that the average of the observed values of the random variable be approximately the same as the expected value [13]. Nevertheless, since the experiment in this particular case is the determination of the *Total PSS Operational Cost,* it is not a repeatable event; therefore the value of $\boldsymbol{E(C_{PSS})}$ must not be considered as the conclusion of the analysis. It is not considered as a repeatable event since every PSS is tailored/engineered for a particular customer.

Moreover, the *Total PSS Operational Cost* considers the total interval time as the contractual time; in other words, the calculated cost is the total cost for the PSS operation along the contractual period. The PSS operation along the contractual period of time refers to the *use stage* of the PSS lifecycle.

Another measure of interest is the *Variance*, which defines the dispersion of the random variable around the mean. If the random variables that compound in the summation of C_{PSS} are independent, their individual contributions are small, and none of them dominate in variance; then *The Central Limit Theorem* (CLT) applies [13], in which case C_{PSS} may be expressed as a *Normal distribution function.*

Another approach is the *Monte Carlo simulation,* in which a random sample from each random variable is taken, and all sampled values are summed. This sum represents one random sample of $\boldsymbol{C_{PSS}}$. This sampling process is repeated sufficiently many times in order to produce an empirical frequency distribution of $\boldsymbol{C_{PSS}}$. From the frequency distribution, an empirical cumulative distribution function of $\boldsymbol{C_{PSS}}$ is established [13]. The most common distributions functions for the total cost that results from the summation of continuous random variables have proven to be the Normal and the Lognormal distributions [12].

After the $\boldsymbol{C_{PSS}}$ distribution function is determined, it is proposed to calculate the probabilities for the *Total PSS Operational Cost* to exceed an expressed value: $\boldsymbol{P(C_{PSS} > x)}$ or $\boldsymbol{P(C_{PSS} > E(C_{PSS}))}$. Now the PSS engineering team will define the desired level of *uncertainty,* which is the probability value, and the $\boldsymbol{C_{PSS}}$ that complies with desired *uncertainty* is considered the *Total PSS Operational Cost.*

5. Exemplification

A simplified example of the proposed *PSS Cost Engineering Probabilistic Method* is presented in this section. It is important to mention that this example has been constructed in order to clarify the most important aspects that the proposed method comprises. It does not represent any particular PSS, industry or application. All following formulas have been retrieved from [13] and [15].

Let us imagine an abstract configuration of a PSS, in which the *product-system* is compounded by three subsystems, and the *service-system* is conformed by two subsystems (see Fig.6).

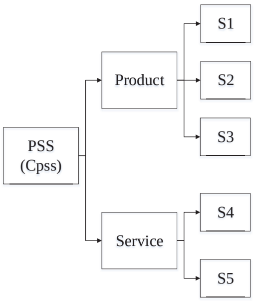

Fig. 6. PSS Configuration

For the identification of the *functional performance probability distribution* $\boldsymbol{f_P(p)}$ for compounding subsystems, it is proposed to carry out a Kolmogorov-Smirnov or Chi-Square tests to determine the distribution that best fits the observed *functional performance* data; theoretical distributions are provided for the purpose of the example. Now the *functional performance relationship* $\boldsymbol{g(p)}$ has to be established.

Note: The scope of this research does not provide the method to define this mathematical relationship, it is a work in progress proposed in the further work section.

Table 1 presents the information devised to illustrate the proposed overall method.

Table 1. Functional Relationships and Distributions

Cost Element S_i	Cost Element Distribution $f_S(s)$	Functional Performance relationship $g(P)$ or $g(S)$	Functional Performance Distribution $f_P(p)$
S_1	$U(3000{,}5200)$	-	-
S_2	-	$S_2 = 2.3(P_{S2})^{2.05}$	$P_{S2} \sim U(200, 220)$
S_3	-	$S_3 = 1.5S_1$	-
S_4	-	$S_4 = 1.42P_{S4}$	$P_{S4} \sim N(500, 20)$
S_5	-	$S_5 = 0.4S_2$	-

Note that the following step is the determination of cost element distribution $\boldsymbol{f_S(s)}$. This determination is known as a *random variable transformation* and can be carried out by several methods [15]. The cost element distribution $\boldsymbol{f_S(s)}$ can also be determined by the relationship among cost elements, like for the cases $\boldsymbol{S_3}$ **and** $\boldsymbol{S_5}$ or it can be already known, as in the $\boldsymbol{S_1}$ cost element. The $\boldsymbol{f_S(s)}$ of $\boldsymbol{S_2}$ and $\boldsymbol{S_4}$ are calculated by the use of Equation 3:

$$\boldsymbol{f_S(s) = f_P\,(g^{-1}(s)) \cdot |d[g^{-1}(s)]/ds|} \tag{3}$$

$$f_{S2}(s2) = \frac{1}{20}\left|\frac{0.324933}{s2^{\frac{21}{41}}}\right| \quad for \quad 2.3(200)^{2.05} \le s2 \le 2.3(220)^{2.05}$$

$$f_{S4}(s4) = \frac{1}{1.42(20\sqrt{2\pi})}e^{-\frac{1}{2}\left(\frac{\frac{s}{1.42}-500}{20}\right)^2} \quad for \quad [-\infty \le s4 \le \infty]$$

Now *Total PSS Operational Cost* equation has to be defined:

$$\boldsymbol{C_{PSS} = S_1 + S_2 + S_3 + S_4 + S_5 = S_1 + S_2 + 1.5S_1 + S_4 + 0.4S_2 = 2.5S_1 + 1.4S_2 + S_4}$$

The expected value of the *Total PSS Operational Cost* is determined, Equation 4 is used:

$$\boldsymbol{E(S) = \int_{-\infty}^{\infty} s f_S(s) ds} \tag{4}$$

$$\boldsymbol{E(C_{PSS}) = E(2.5S_1 + 1.4S_2 + S_4) = 2.5E(S_1) + 1.4E(S_2) + E(S_4)}$$

$$\boldsymbol{E(C_{PSS}) = \$10,250 + \$185,677.8 + \$710 = \$196,637.8}$$

The next step is the calculation of the *Total PSS Operational Cost Variance,* since $\boldsymbol{S_1, S_2}$ **and** $\boldsymbol{S_4}$ are independent random variables, then from Equation 5 and properties of variance:

$$\boldsymbol{Var(X) = E(X^2) - [E(X)]^2} \tag{5}$$

$$\boldsymbol{Var(C_{PSS}) = Var(2.5S_1) + Var(1.4S_2) + Var\ (S_4) = 2.5^2Var(S_1) + 1.4^2Var(S_2) + Var\ (S_4)}$$

$$\boldsymbol{Var(C_{PSS}) = \$2,520,833.313 + \$109,130,587.2 + \$807 = \$111,652,227.5}$$

If the individual costs of the PSS subsystems were dependent, the variance of the PSS total cost is determined by Equation 6:

$$\boldsymbol{Var(C_{PSS}) = \sum_{i=1}^{n} Var(S_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \rho_{S_i,S_j}\sigma_{S_i}\sigma_{S_j}} \tag{6}$$

Where, the term ρ is known as the Pearson correlation coefficient…"*It is the traditional statistic to measure the degree to which two random variables correlate/covary… it measures the strength of the linear relationship*" [12]. The mathematical expression is given by Equation 7:

$$\boldsymbol{Corr(X,Y) = \rho_{X,Y} = (E(XY) - \mu_X\mu_Y)/\sigma_X\sigma_Y} \tag{7}$$

It is important to notice that for this particular case the *Central Limit Theorem* does not apply given the fact that there is a dominant random variable in the variance of the *Total PSS Operational Cost.* Therefore the assumption that $\boldsymbol{C_{PSS} \sim N(196637.8, \sqrt{111652227.5})}$ cannot be made. In order to obtain more information about the probability distribution of interest a *Monte Carlo Simulation* has been carried out with a total of 5,000 simulated points. Results are presented in Fig. 7.

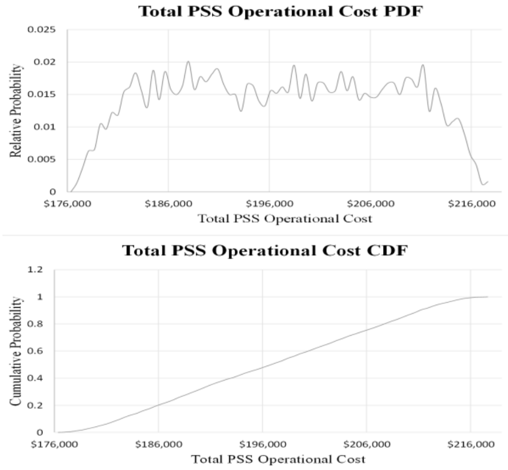

Fig. 7. Monte Carlo Simulation

By the shape of both the PDF and CDF it is concluded that the *Total PSS Operational Cost* is distributed as a *trapezoidal random variable.* Now the parametrization of such distribution must be made in accordance with the calculated expected value and variance of *Total PSS Operational Cost* and the observed range of simulated values form the Monte Carlo simulation.

The parametrization that best fit both aspects is given as:

$$\boldsymbol{C_{PSS} \sim Trap(a, m1, m2, b) = Trap(\$175879.08, \$181183.77, \$212091.83, \$217396.52)}$$

From trapezoidal distribution [13] it is observed that with such parametrization:

$$\boldsymbol{E(C_{PSS}) = \frac{((m2+b)^2 - m2b) - ((a+m1)^2 - am1)}{3(m2+b-a-m1)} = \$196,637.8}$$

$$\boldsymbol{Var(C_{PSS}) = \frac{(m2^2+b^2)(m2+b) - (a^2+m1^2)(a+m1)}{6(m2+b-a-m1)} - [E(C_{PSS})]^2 = \$111,625,227.11}$$

Now that the distribution is known, we calculate the following set of probabilities in order to get an insight into how the *Total PSS Operational Cost* behaves:

$$\boldsymbol{P\big(C_{PSS} > E(C_{PSS})\big) = 1 - F(E(C_{PSS})) = 1 - (2E(C_{PSS}) - a - m1)/((m2+b-a-m1)\,) = 0.5}$$

$$P(C_{PSS} > E(C_{PSS}) + \sigma) = 1 - F(E(C_{PSS}) + \sigma) = 1 - (2(E(C_{PSS})) + \sigma) - a - m1)/((m2 + b - a - m1)) = 0.2082$$

It is also recommended to define the selling price by means of the *Total PSS Operational Cost* and the assigned uncertainty to a certain desired gross margin. For example, if the PSS provider desires to obtain at least a 25% gross margin with an assigned 90% of certainty, what should be the PSS price if operational costs are known to represent 85% of total cost?

$$P\left(C_{PSS} \leq c_{pss}\right) = 0.9 = F(c_{PSS}) = (2(C_{PSS})) - a - m1)/((m2 + b - a - m1))$$

$$c_{PSS} = \$211,122.93$$

$$PSS\ price = \$211,122.93/0.85(0.75) = \$331,173.22$$

6. Discussion

The proposed PSS cost engineering method offers a way to determine the operational cost of every compounding PSS subsystems by means of its *functional performance,* therefore it applies regardless PSS configuration (type and quantity of products, type of services, and quantity of services). Thus, the scope of the PSS cost engineering method comprises the whole spectrum of the most broadly accepted PSS typology: product-oriented, use-oriented, and result-oriented.

For example, a photocopier, if it is commercialized under the *product-oriented scheme,* the PSS cost engineering method will only be needed to define the service subsystems costs (e.g. product installation, training, maintenance, repairs, etc.). This does not imply that the product is not considered in the PSS cost engineering method (since its *functional performance* impacts on the services costs), but its cost is not plugged into the *Total PSS Operational Equation.* If now the photocopier PSS offering is commercialized under a *use-oriented scheme,* the PSS cost engineering method must include other product subsystems such as sensors that monitor the performance of the product. The PSS cost engineering method does not present restrictions on the number of product subsystems or service subsystems, subsystems adequate in function of the PSS scheme. Finally, when considering a PSS commercialization under a *result-oriented* scheme, special attention must be paid to the *functional performance distribution intervals* in order to comply with customer requirements. The PSS cost engineering method determines the cost by given values of performance, and these values should be more severe than in other schemes.

7. Conclusions and Further Work

Current efforts for the cost estimation of a PSS has faced great complexity due to the significant level of *uncertainty* that actual approaches entail. It is believed that the level of *uncertainty* highly depends on the applied *Ontology.* This research proposes a probabilistic method to determine the *Total Operational Cost of a PSS* and to capture the *aleatory uncertainty* of the cost determination. *Note:* For addressing the *epistemic uncertainty* of a PSS please consult [2].

The introduced probabilistic method is based on a *System Cost Uncertainty Analysis,* and proposes the use of *functional performance* as a random variable, for both the representation of PSS subsystems interconnections, and the PSS subsystems cost determination. Since one of the most important outputs of the method is the *Total PSS Operational Cost distribution*, other applications of the method can be pricing, risk mgmt., and system simplification.

Further work must be carried out in order to propose methods to determine $\boldsymbol{g(p)}$, which is the mathematical expression that describes: how *cost* is related to the *functional performance* of the subsystem? The proposed structure is part of a research work in progress, in which the *Total PSS Operational Cost random variable* will be placed within a bivariate random vector with PSS functionality as the other random variable. Together the *cost* and the *functionality* of the PSS are used in order to obtain a *Joint Probability Model.* The main purpose of this approach is to analyze the PSS cost behavior by the given knowledge of its functionality.

References

[1] Settanni E, Thenent N, Newnes L. System Modeling: A Foundation for Costing Through-Life Availability Provision. Product Lifecycle Management for Society, *IFIP AICT*, Springer 2013, Vol. 409:48-57.

[2] Estrada A, Romero D. A System Quality Attributes Ontology for Product-Service Systems Functional Measurement based on a Holistic Approach. 8th IPSS Conf. on Product-Service Systems across Life Cycle 2016.

[3] Erkoyuncu J, Roy R, Shehab E, Wardle P. Uncertainty Challenges in Service Cost Estimation for Product-Service Systems in the Aerospace and Deference Industries, CIRP 1st IPS2 Conf., 2009:200-207.

[4] Van Ostaeyen J, Van Horenbeek A, Pintelon L, Duflou JR. A Refined Typology of Product-Service Systems based on Functional Hierarchy Modeling. *Journal of Cleaner Production* 2013; 51(15):261-276.

[5] Baines T, Lightfoot H, Evans S, et al. SOTA in Product Service Systems. The Institution of Mechanical Engineers Part B 2007; 221(10):1543-52.

[6] Keuneke A. Device Representation – The Significance of Functional Knowledge. *IEEE Expert* 1991. pp. 22-25.

[7] Hollmann J. Required Skills and Knowledge of Cost Engineering. AACE International Recommended Practice No. 11R-88, 2006:1-22.

[8] Stewar RD, Wyskida RM, Johannes JD. Cost Estimator's Reference Manual. 2nd Ed. Wiley Interscience 1995.

[9] Walker WE, Harremoës P, Rotmans J, et al. Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. *Integrated Assessment* 2003; 4(1):5-17.

[10] Erkoyuncu J, Roy R. Understanding Service Uncertainties in Industrial Production-Service System Cost Estimation. *International Journal of Advanced Manufacturing Technology* 2010; 52(9):1223-1238.

[11] Goh Y, Newnes L, Settanni E, Thenent N, Parry G. Addressing Uncertainity in Estamating Cost for a PSS Delivering Availability: Epistemology and Ontology. Springer 2015.

[12] Dekker S. Drift into Failure: From Hunting Broken Components to Understanding Complex Systems. Ashgate Pub., Burlington, VT 2011

[13] Garvey PR. Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective. Chapman and Hall/CRC; 2nd Ed. 2015.

[14] Garvey PR. Modeling Cost and Schedule Uncertainties: A WBS Perspective. Military Operations Research 1996; 2(1):37-43.

[15] Casella, G, Berger, R. Statistical Inference. Brooks/Cole 2002, 2nd Ed.: 47-68.