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A PRACTICAL AND PROACTIVE WAY OF MANAGING WEIGHT & CENTER OF GRAVITY UNCERTAINTY USING THE SUCCESSIVE PRINCIPLE

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Abstract

One of the challenges in mass properties is how to handle the uncertainty in an early stage estimate of weight and center of gravity (CG) and its impact throughout the life of the project. Risk is sometimes defined as the product of consequence multiplied by uncertainty, and for many shipbuilding projects the consequence of missing the mark on either the weight or CG can be dramatic. That makes reducing uncertainty essential to avoiding a high-risk project.

Dr. Steen Lichtenberg started as early as the 1970's to develop a method for proactive management of uncertainty using the Successive Principle. The method is a practical way to manage opportunities and risk. The underlying philosophy states that realism in forecasts requires a qualitative phase as well as a quantitative phase. In the qualitative phase, an analysis group of people should be established, while the quantitative phase should establish a basic structure of main items, followed by a systematic detailing process and an action plan.

While the method typically handles uncertainties related to the economics of large projects, this paper will look at how the principles and processes involved can be applied to the weight and CG challenges during ship design and construction. A general introduction to the Successive Principle will be given, the basic applications will be presented, and discussions and examples of use cases will be included. The goal is to add another tool to the toolbox of the weight engineer to help ensure successful projects.

> "If you start with certainty
> You will finish with doubt
> If you start with uncertainty
> You will finish with certainty"
> *Sir Francis Bacon*, philosopher (1561-1626)

> "Uncertainty has several names
> For the fool, it does not exist
> For the afraid, it means risk
> For the brave it means also opportunities"
> Freely from *Victor Hugo*, author (1802-1885)

Introduction

Nothing is Certain

One could argue with reason that no future event can be predicted with an absolute certainty, but rather with a degree of likelihood, low or high. We all face uncertainty to some degree constantly every day, no matter who we are or what we do.

Luckily the vast majority of events in our everyday lives fall into one of two categories: either the likelihood of the event is so high that we for practical reasons can treat it like a certainty, or the consequence of the worst scenario outcome may be of little or no negative impact (or even positive impact) to us, making it negligible.

However, sometimes you may face decisions connected with considerable risk (here defined as the product of uncertainty and consequence). In this case, reducing the uncertainty will help you to make the right choices moving forward. Many projects fall into this category, related to economics, schedule, technical issues, or a combination of these.

Challenges with the Classical Approach

Science has provided us with theory and a large set of statistical tools that can help us deal with uncertainty. However, classical statistical theory and methods are not well suited for many projects facing uncertainty. This is especially true when facing economic, schedule, or technical challenges.

This is because in general, classical statistical methods require either a large set of related historical data and/or detailed knowledge about the statistical nature of the event(s). For many projects, especially the "one-off" type of projects, one or both of these pre-requisites is missing.

A More Practical Way

The challenges the classical statistical methods present make it necessary to look for alternative methods for handling uncertainty. The Successive Principle is such an alternative method. It draws on the competence and knowledge of people with insight into the matter to be analyzed and uses calculation and quantification principles to establish a range of probability as a decision basis for management.

What This Paper Will Address and What It Will Not Address

This paper will describe the use of the Successive Principle to deal with risk by lowering the uncertainty related to weight estimations. It will explain the main principles of the Successive Principle in a general way and then specifically look at its application towards the estimation of weight for a new shipbuilding project. For simplicity we disregard the center of gravity, but we do not see any reason the same approach could not be used for this as well.

This paper will look at the Successive Principle applied to the challenges of a project from a technical point of view. It will not look at uncertainty related to economics or time and schedules, although the Successive Principle is very well suited to take on these tasks as well. Neither will this paper try to explain or describe the underlying statistical theory or terminology presented here. For this we refer to general sources of statistical theory.

The paper is a brief introduction to the Successive Principle, and most of the theory described here is from the book "Proactive Management of Uncertainty using the Successive Principle" by Dr. Steen Lichtenberg [1]. We refer the interested reader to this book for more in-depth information.

Successive Calculation and Weight Estimation – the Goal of This Paper
Several projects where the Successive Principle was applied are documented in the literature, but all were related to economics, time/scheduling issues, or a combination of these.

This goal of this paper is to explore the possibility of using the Successive Principle for weight estimation projects.

The Successive Principle

Background
In the early 1970s, several academics were working on solutions to the issues set forth in the introduction of this paper. One of the leading people in this work was Dr. Steen Lichtenberg from Denmark. During the '70s and '80s, several papers and books were written on the subject, and from this work the theory of the Successive Principle emerged. Numerous large and very large projects have since benefited from the method and official reports have been written to document the success of the approach [2].

The Goals of the Successive Principle
The goals of the Successive Principle are to provide procedures and tools to handle uncertainty in an efficient manner and give the ability to make reliable forecasts, and further to present a list of 'top-ten' items for improvement along with an action plan.

The Basic Philosophy
The basic philosophy of the Successive Principle is to look at handling uncertainty as a necessary and important part of a project, and as a tool not just to reduce risk, but also to find new opportunities and improvements for the project. The Successive Principle has two main phases; a qualitative phase and a following quantitative phase, both of which will be presented below.

The Qualitative Phase

Establishing an Analysis Group
The first thing that needs to be done to start the process of the Successive Principle is to establish an analysis group for the project. This group should consist of people that have good insight and broad knowledge about the project and subjects related to the project.

However, it is of the utmost importance that this group has a broad and varied composition of people. One should not make the mistake of only having subject matter experts, although they should certainly be part of the group. Make sure the group is diverse regarding background and competence, even, as far as possible, making sure there is a good mix of gender, ages, and personality types. A group would have at least 4 people, but not more than 25.

It is very important to establish an environment for the group where everyone feels they can speak freely, including on subjects that go to the heart of the organization and leadership.

Finally, the group needs a leader, someone with great insight both into the project and the Successive Principle, to lead the group in its work.

Establish Consensus on the Task

The first thing the analysis group should do is to discuss thoroughly, describe, and fully agree upon the goals, objectives, and pre-set conditions for the project. The goals should be formulated quite concretely, often related to one or more specific key parameters. Typical parameters would be for performance, profitability, and cost or time schedule for the project, and a typical goal would be to find expected values with corresponding uncertainties for the parameter(s).

Furthermore, fixed pre-conditions must be collected and summarized. Both formal and as much informal information as possible should be collected. Fixed pre-conditions can be anything from currency and interest rates, units and materials, to drawings and project specifications.

Finding the Overall Influences

The next step for the group is to enter a brainstorming session to identify all general sources of uncertainty related to the project. This could typically be 50-100 issues and they should all be described in sufficient detail. This list should include social and organizational matters as well as the technical matters. These issues are called "general issues."

Now these general issues need to be reduced, or categorized into groups of "Overall Influences" that are of a more practical size. Strive to get a number of "overall influence" groups to a range of eight to 15. It is very important that these groups are statistically independent as far as possible. The statistical independence is of great importance to the method of Successive calculation presented later in this paper.

A practical way to find these groups is to let everyone in the group contribute one or two headings that they feel capture the most important uncertainty issue, inspired by the list of general issues. A last group may typically be "any other aspects" containing all issues that did not fit into any specific group.

Dual Definitions of the Overall Influences

The final task in the qualitative phase is to define dual definitions, called "base case" and "actual future case," for the Overall Influences.

The base case is the closest you can get to a known normal situation for the Overall Influence; in other words it should describe a typical or average situation for the Overall Influence.

The actual future case should describe what you believe is special or unique for this particular project, or the difference between this particular project and a "base case" project. Note that this is not necessarily a negative deviation; it may well be positive or even both negative and positive.

With the base case and actual future case described for each Overall Influence, the qualitative phase ends and the quantitative phase can start.

The Quantitative Phase

The Work Breakdown Structure

The long list of general issues from the qualitative phase will be too large and unstructured to deal with in the quantitative phase, so these needed to be grouped into fewer and statistically independent Overall Influences. Yet to perform a quantitative analysis on the few Overall Influences as they are would be too simplistic. Appropriate items (often items related to something "physical") of the Overall Influences should therefore be broken into an appropriate hierarchical work breakdown structure.

Any work breakdown structure that seems applicable may be used, with the only condition that the various groups must be reasonably statistically independent. Again, the statistical independence of the groups is important for the uncertainty calculation methods set forth later in the paper. We have now reached the stage where we will start to say something about the expected values and uncertainty of each of the various groups.

Cancellation Effects

There are several reasons why a work breakdown structure is a good approach. It can simplify something that is too complex into more manageable parts, and it can provide a clearer picture and better understanding of an item.

But perhaps the most important benefit of the work breakdown structure is the cancellation effects that are obtained by separating a group into statistically independent subgroups. These effects follow from statistical theory giving that the standard deviation of a group equals the square root of the sum of the squared standard deviations for the subgroup.

$$S_{total} = \sqrt{(S^2_{Subgr.1}} + S^2_{Subgr.2} + S^2_{Subgr.3} + \cdots + S^2_n)$$

The effect can be illustrated as follows:

Consider a group with total value of 300 and a standard deviation of 10 % = 30. If you divide this group into into 3 subgroups with a value of 100 each, and with a standard deviation of 10 % = 10 for each of the groups, you have now reduced the total standard deviation for the group total from 30 to 17.3:

$$S_{total} = \sqrt{(10^2_{Subgr.1}} + 10^2_{Subgr.2} + 10^2_{Subgr.3}) = 17.3 \ \ (or\ from\ 10\ \%\ to\ 5.7\ \%)$$

This is an extremely powerful way of reducing uncertainty.

Quantification – Most likely, Minimum, and Maximum value

The quantification process starts with establishing the following values for each group: Most likely, minimum, and maximum value. These values should be established based upon experience, historical relatable data, and knowledge of the issue.

The most likely value is self-explanatory, but what do we mean with the minimum and maximum values? The guideline for the minimum value should be the value (or less) that you think would happen in only 1 out of 100 cases. Likewise, the guideline for the maximum value should be the value that would be reached or surpassed in only 1 out of 100 cases.

These values, the most likely, minimum, and maximum value, form the basis of what is called the "Triple Estimate."

Calculating the Mean Value from the Triple Estimate

According to the subjective probability theory, the triple evaluation of an item is considered a stochastic variable which can be dealt with according to normal and well-documented statistical rules. Experiments and theoretical findings have led to the assumption that a mean value for most parameters can be calculated with sufficient accuracy by the following formula [3]:

The mean value $M = (Minimum + 3 \times Most\ Likely + Maximum)/5$

Negative and positive values can be used for any of the estimates. When the minimum and maximum values are symmetrical around the most likely value, the mean value will equal the most likely value.

The mean values for all groups are added together to estimate the mean value for the grand total for the project.

Calculating Uncertainty from the Triple Estimate

The standard deviation of the mean value for a group is calculated with sufficient accuracy by using the following formula [3]:

Standard deviation $S = (Maximum – Minimum)/5$

The uncertainty of the grand total for n number of groups is calculated from the following formula:

$$S = \sqrt{(S_1^2 + S_2^2 + S_3^2 + \cdots + S_n^2)}$$

The S^2 (squared S) value in the Successive Principle is called the Product Number, and it is used to rank the groups according to the overall contribution to the uncertainty of the grand total. This ranking will be used to prioritize the groups will need further attention to improve the overall results.

The Use of Factors

Sometimes a group value is a result of factors multiplied together. In this case, the factors are treated the same way as a single group value (with most likely, minimum, and maximum values); however, the standard deviation *S* should be expressed as a relative standard deviation by dividing it by the mean value M (S/M %). According to the theory, these relative standard deviations are multiplied with the resulting M to obtain the local contribution to the overall standard deviation for the group. This is shown in the "Case Study" later in this paper.

Overall Correction Factors as Percentage

Experience has shown that people have a tendency to unconciously evaluate the range of uncertainty for the overall correction factors as a percentage of the base case totals [1]. This means that the values added from the other correction factors are not considered, and this may lead to an overall correction that is too low. To account for this, correction factors are better handled by using factors and multiplying by the base case summary, instead of absolute values.

Warnings and Pitfalls

The overall results of the Successive Principle obviously depend upon the quality of the work of the analysis group. Are all of the important Overall Influences taken into account? And, how good are the triple estimate values that are set for the groups? There are many pitfalls here, but this paper will only address two of the most common ones and suggest a solution to them.

The first one is the tendency to listen too much to other people instead of trusting one's own instinct when values are given for the triple estimate. The solution to this is simply to make all participants of the group set the values secretly after the discussion of the issues, and then an average value of the values submitted by the group is selected as the most likely value.

The second one is the tendency to underestimate the extreme values. Studies have shown that, in general, people give a range that is too narrow when they are asked to set the minimum and maximum values. One solution to this is to set the minimum and maximum values to the most extreme values as submitted by the group's individuals to represent the minimum and maximum values.

Case Study

Estimating the Weight of a New Aircraft Carrier

The Navy of Tuvalu has decided that their monohull aircraft carriers will no longer do and are looking to build a catamaran (twin-hull) aircraft carrier. Tuvalu Shipbuilding Company Ltd is tasked with finding the weight of the new carrier at an early design stage.

A mixed group of competent people, engineers and builders, optimists and pessimists, young and old, male and female are put together and decide to use the Successive Principle for the task.

Overall Influences for the Aircraft Carrier

A list of more than 50 general issues are grouped together into the Overall Influences presented in table 1, and analyzed with regard to the base case and the actual future case. The result follows here:

Table 1: Case Study, Overall Influences of the Weight of the new Aircraft Carrier

No	Overall Influences	Base case	Actual future case
1	Basic Weight Estimation	Good historical data describing the weight/parameter relationship	New design will give new ratio in many areas
2	Client change request	Various change requests during construction	Same
3	Material type & quality changes	Amount of high-strength steel normally known	Amount may change with new design
4	Equipment changes	Equipment in line with previous design	New design may require new equipment in some cases
5	Machinery changes	Little or no change from previous design	New design may give machinery changes
6	Design change	Little or no design changes	More design changes than usual
7	Class Society	Normally small or no influence	May require some extra strengthening
8	Other issues	Relatively small impact	Unknown

The base case represents the situation if they were to build yet another monohull aircraft carrier, while the actual future case outlines the new challenges with the new catamaran design.

First Round of Triple Estimates

From the table of Overall Influences, the next step is to describe all base cases and future actual cases and find the minimum value, maximum value, and most likely value for all cases, and further to apply the triple estimate to calculate the mean value (M), the standard value (S), and the Product number (P). The mean value M is calculated using the formula *M = (Minimum + 3 x Most Likely + Maximum)/5*, while the standard deviation is approximated by the formula *S = (Maximum – Minimum)/5* and the Product value is calculated from *P = S x S.*

Table 2: First Triple Estimate

Text		Triple estimate			Items [k tons]		Product
No	**Base case items**	**Min.**	**Likely**	**Max.**	**M**	**S**	**P = SxS**
1	Basic Weight Estimation	72	80	95	81.4	4.6	21.2
2	Client change request	1	4	8	4.2	1.4	2.0
3	Material type/quality changes	0	1	3	1.2	0.6	0.4
4	Equipment changes	1	3	7	3.4	1.2	1.4
5	Machinery changes	0	2	5	2.2	1.0	1.0
6	Design change	2	4	7	4.2	1.0	1.0
7	Class Society	0	0	3	0.6	0.6	0.4
8	Other issues	0	1	2	1.0	0.4	0.2
Sum base case		**Std dev**	**5.3%**		**98.2**	**5.2**	**27.4**
No	**Overall correction items**						
1	Basic Weight Estimation	5	18	35	18.8	6.0	36.0
2	Client change request	0	8	16	8.0	3.2	10.2
3	Material type/quality changes	0	4	10	4.4	2.0	4.0
4	Equipment changes	1	5	12	5.6	2.2	4.8
5	Machinery changes	2	6	15	7.0	2.6	6.8
6	Design change	1	4	8	4.2	1.4	2.0
7	Class Society	0	4	8	4.0	1.6	2.6
8	Other issues	1	3	7	3.4	1.2	1.4
Sum correction values		**Std dev**	**14.9%**		**55.4**	**8.2**	**67.8**
Total sum		**Std dev**	**6.4%**		**153.6**	**9.8**	**95.2**

The result from this work shows a mean value of the total weight of the new aircraft carrier of 153,600 tons, and with a standard deviation of 9,800 tons, or 6.4 %. However, according to the theory of the Successive Principle, using absolute values for the overall correction items will, as discussed earlier in this paper, give a correction that is too small, as people intuitively set corrections related to the base total and not the grand total. A new table must therefore be set up, this time using correction factors and not correction values.

The First Triple Estimate using Correction Factors

In the table below, the correction values from the table above have been converted to correction factors. The new table now becomes:

Table 3: Correction Factors

Text		Triple estimate			Factors			Items [k tons]			Product
No	**Base case items**	**Min.**	**Likely**	**Max.**	**m**	**s**	**s/m [%]**	**M**	**S(0)**	**S**	**P = SxS**
1	Basic Weight Estimation	72	80	95				81.4	4.6	7.9	62.0
2	Client change request	1	4	8				4.2	1.4	2.4	5.7
3	Material type/quality changes	0	1	3				1.2	0.6	1.0	1.1
4	Equipment changes	1	3	7				3.4	1.2	2.1	4.2
5	Machinery changes	0	2	5				2.2	1.0	1.7	2.9
6	Design change	2	4	7				4.2	1.0	1.7	2.9
7	Class Society	0	0	3				0.6	0.6	1.0	1.1
8	Other issues	0	1	2				1.0	0.4	0.7	0.5
Sum base case		**(Std dev**	**9.1%**	**)**				**98.2**		**9.0**	**80.4**
No	**Overall correction items**										
1	Basic Weight Estimation	1.05	1.18	1.36	1.19	0.06	5.1%			8.6	74.3
2	Client change request	1.00	1.08	1.16	1.08	0.03	3.0%			5.1	25.7
3	Material type/quality changes	1.00	1.04	1.10	1.04	0.02	1.9%			3.3	10.7
4	Equipment changes	1.01	1.05	1.12	1.06	0.02	2.1%			3.6	12.7
5	Machinery changes	1.02	1.06	1.15	1.07	0.03	2.5%			4.2	17.3
6	Design change	1.01	1.04	1.08	1.04	0.01	1.4%			2.3	5.3
7	Class Society	1.00	1.04	1.08	1.04	0.02	1.6%			2.6	6.9
8	Other issues	1.01	1.03	1.07	1.03	0.01	1.2%			2.0	3.9
Sum correction factors		**(Std dev**	**17.9%**	**)**				**69.9**		**12.5**	**156.8**
Total sum		**(Std dev**	**9.2%**	**)**	**1.71**			**168.1**		**15.4**	**237.2**

The transformation from correction values to correction factors happens like this: If we consider the correction values for item no 1, Basic Weight Estimation, the values min/likely/max were 5/18/35. We convert them to factors by dividing them by the base case total and adding 1; this gives:

$$\text{Minimum} = 1 + 5/98.2 = 1.05$$
$$\text{Most likely} = 1 + 18/98.2 = 1.18$$
$$\text{Maximum} = 1 + 35/98.2 = 1.36$$

Next, mean factor (m), and standard deviation for factors (s) is calculated using the same formulas as for mean values M and standard deviation for values S. Now the factor means (m) are multiplied to get the overall total correction factor. In our example this is

$$1.19*1.08*1.04*1.06*1.07*1.04*1.04*1.03 = 1.71$$

This overall correction factor then gets multiplied with the base case total to give the new grand total:

$$1.71 * 98.2 = 168.1$$

Further, each of the standard deviations (S) from the first table are transferred to the column S(0) and are also multiplied by the correction factor to get a new standard deviation. For basic case item no 1 the standard deviation is corrected to:

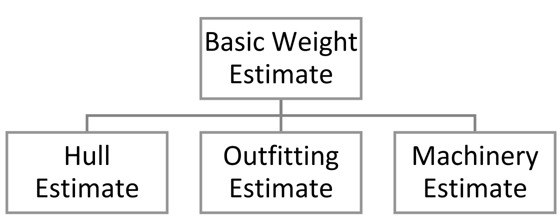
$$4.6 * 1.71 = 7.9$$

The same steps are followed for the other Overall Influence items. Our new corrected, more realistic estimate now shows a total weight of 168,000 tons with a standard deviation of 15,400 tons, or 9.2 %.

Second Round of Triple Estimate

From the Priority numbers of table 3 we can clearly see that the largest contributor by far to the uncertainty is the "physical" weight estimation of base case no 1 and correction item no 1. This is where we need to focus to improve the estimate. We therefore apply the method of a work breakdown structure to this item. For simplicity we will only divide item no 1 into one single set of subgroups and stop there. In a more realistic example, a more complex structure is likely to be applied. In this particular example, maybe most or all parts of a shipbuilding work breadown structure like SFI or SWBS would be used.

However, in this example we will only divide the "physical" item no 1 into the following subgroups:



The new table will now look like this:

Table 4: Second Round of Triple Estimate, introducing work breakdown structure for Item no1

	Text	Triple estimate			Factors			Items [k tons]			Product
No	**Base case items**	**Min.**	**Likely**	**Max.**	**m**	**s**	**s/m [%]**	**M**	**S(0)**	**S**	**P = SxS**
1	Basic Weight Estimation										
1.1	- Hull Estimate	53	58	66				58.6	2.6	4.4	19.4
1.2	- Outfitting Estimate	9	12	16				12.2	1.4	2.4	5.6
1.3	- Machinery Estimate	6	8	10				8.0	0.8	1.4	1.8
2	Client change request	1	4	8				4.2	1.4	2.4	5.6
3	Material type/quality changes	0	1	3				1.2	0.6	1.0	1.0
4	Equipment changes	1	3	7				3.4	1.2	2.0	4.1
5	Machinery changes	0	2	5				2.2	1.0	1.7	2.9
6	Design change	2	4	7				4.2	1.0	1.7	2.9
7	Class Society	0	0	3				0.6	0.6	1.0	1.0
8	Other issues	0	1	2				1.0	0.4	0.7	0.5
Sum base case		**(Std dev**	**7.0%**	**)**				**95.6**		**6.7**	**44.9**
No	**Overall correction items**										
1	Basic Weight Estimation				1.17						
1.1	- Hull Estimate	1.03	1.08	1.15	1.08	0.02	2.2%			3.6	12.9
1.2	- Outfitting Estimate	1.02	1.03	1.08	1.04	0.01	1.2%			1.9	3.5
1.3	- Machinery Estimate	1.02	1.05	1.08	1.05	0.01	1.1%			1.9	3.4
2	Client change request	1.00	1.08	1.17	1.08	0.03	3.1%			5.0	25.0
3	Material type/quality changes	1.00	1.04	1.10	1.05	0.02	2.0%			3.2	10.5
4	Equipment changes	1.01	1.05	1.13	1.06	0.02	2.2%			3.5	12.4
5	Machinery changes	1.02	1.06	1.16	1.07	0.03	2.5%			4.1	16.8
6	Design change	1.01	1.04	1.08	1.04	0.01	1.4%			2.3	5.2
7	Class Society	1.00	1.04	1.08	1.04	0.02	1.6%			2.6	6.8
8	Other issues	1.01	1.03	1.07	1.04	0.01	1.2%			2.0	3.9
Sum overall correction factors		**(Std dev**	**15.1%**	**)**				**66.4**		**10.0**	**100.3**
Total sum		**(Std dev**	**7.4%**	**)**	**1.69**			**162.0**		**12.1**	**145.2**

We can see cleary from the Product numbers in the new table that we have reduced the uncertainty for item no 1 significantly by dividing up the “physical” item even into the smallest of work breakdown structures (3 subgroups).

Note that the divided correction group now gives local correction points where the overall contribution of m (mean factor) is calculated from multiplying the local likely values (in this case 1.08*1.03*1.05 = 1.17) to give the new global contribution factor m. However, the local uncertainties are not contributing to the overall correction point, but rather giving a direct contribution to the Product number.

Third Round of Triple Estimate: Introducing Factors for Items

As mentioned earlier, a more realistic case would have continued to break the new subgroups into further and more subgroups, but in this simple example we will stop here.

At the last level of groups, there is one more step to use to even further increase the accuracy of the estimation. This is to introduce factors for items, or an estimation formula if you like, where uncertainty is given to the factors in the same way as they were given to the correction factors. This gives yet another level of splitting an uncertain number to reduce the overall uncertainty by the cancellation effects obtained.

In this example, the formula we will introduce for the subgroups Hull and Outfitting is the formula

$$W = k1 * V \text{ and } W = k2 * A$$

Where W is the weight, V is a volume factor, A is an area factor and k1, k2 is the ratio factor (density) of weight units per volume units and weight units per area units.

Introducing this to the result will give the final table in this case as follows:

Table 5: Third Round of Triple Estimate - Introducing Factors for Items

	Text	Triple estimate			Factors			Items [k tons]			Priority
No	**Base case items**	**Min.**	**Likely**	**Max.**	**m**	**s**	**s/m [%]**	**M**	**S(0)**	**S**	**P = SxS**
1.1	- Hull Estimate							60.6			
1.1.1	*- - Volume [1000 m3]*	*265*	*272*	*284*	*273.00*	*3.80*	*1.4%*		*0.8*	*1.4*	*2.1*
1.1.2	*- - [tons] per m3]*	*0.21*	*0.22*	*0.24*	*0.22*	*0.01*	*2.7%*		*1.6*	*2.8*	*7.7*
1.2	- Outfitting Estimate							12.5			
1.2.1	*- - Area [1000 m3]*	*144*	*148*	*156*	*148.80*	*2.40*	*1.6%*		*0.2*	*0.3*	*0.1*
1.2.2	*- - [tons] per [m3]*	*0.07*	*0.08*	*0.11*	*0.08*	*0.01*	*9.5%*		*1.2*	*2.0*	*4.1*
1.3	- Machinery Estimate	6	8	10				8.0	0.8	1.4	1.8
2	Client change request	1	4	8				4.2	1.4	2.4	5.7
3	Material type/quality changes	0	1	3				1.2	0.6	1.0	1.0
4	Equipment changes	1	3	7				3.4	1.2	2.0	4.2
5	Machinery changes	0	2	5				2.2	1.0	1.7	2.9
6	Design change	2	4	7				4.2	1.0	1.7	2.9
7	Class Society	0	0	3				0.6	0.6	1.0	1.0
8	Other issues	0	1	2				1.0	0.4	0.7	0.5
Sum base case		**(Std dev**	**6.0%**	**)**				**97.9**		**5.8**	**34.0**
No	**Overall correction items**										
1	Basic Weight Estimation				1.18						
1.1	- Hull Estimate				1.09						
1.1.1	*- - Volume [1000 m3]*	*1.03*	*1.04*	*1.07*	*1.04*	*0.01*	*0.8%*			*1.3*	*1.6*
1.1.2	*- - [tons] per [m3]*	*1.01*	*1.05*	*1.11*	*1.05*	*0.02*	*1.9%*			*3.2*	*10.0*
1.2	- Outfitting Estimate				1.03						
1.2.1	- - Area [1000 m3]	1.01	1.02	1.03	1.02	0.00	0.4%			0.7	0.4
1.2.2	*- - [tons] per [m3]*	*1.00*	*1.01*	*1.03*	*1.01*	*0.01*	*0.6%*			*1.0*	*1.0*
1.3	*- Machinery Estimate*	*1.02*	*1.05*	*1.08*	*1.05*	*0.01*	*1.1%*			*1.9*	*3.6*
2	Client change request	1.00	1.08	1.16	1.08	0.03	3.0%			5.0	25.3
3	Material type/quality changes	1.00	1.04	1.10	1.04	0.02	2.0%			3.3	10.6
4	Equipment changes	1.01	1.05	1.12	1.06	0.02	2.1%			3.5	12.5
5	Machinery changes	1.02	1.06	1.15	1.07	0.03	2.5%			4.1	17.0
6	Design change	1.01	1.04	1.08	1.04	0.01	1.4%			2.3	5.2
7	Class Society	1.00	1.04	1.08	1.04	0.02	1.6%			2.6	6.8
8	Other issues	1.01	1.03	1.07	1.03	0.01	1.2%			2.0	3.9
Total sum		**(Std dev**	**6.9%**	**)**	**1.70**			**166.3**		**11.5**	**131.8**

The M values for the base case sub-items are calculated from multiplying the factors, and their uncertainty is used directly for Product numbers.

This will be the final step of calculations in this example. We end with a total weight of of 166,300 tons and an uncertainty of 11,500 tonnes or 6.9 %.

But the end of the calculation is not the end of the method of the Successive Principle. The final step is the “top-ten” list and action plan.

The Top-Ten List and the Action Plan

The final step of the method is to produce and present the results in the form of a “top-ten most uncertain list” and an action plan.

For our example, the top-ten list will look like this:

Table 6: The Top-Ten List

No	**Text**	**Item type**	**Priority**
2	Client change request	*Correction Item*	25.3
5	Machinery changes	*Correction Item*	17.0
4	Equipment changes	*Correction Item*	12.5
3	Material type/quality changes	*Correction Item*	10.6
1.1.2	Hull weight - [k tons] per [k m3]	*Correction Item*	10.0
1.1.2	Hull Weight - [k tons] per [k m3]	*Base case item*	7.7
7	Class Society	*Correction Item*	6.8
2	Client change request	*Base case item*	5.7
6	Design change	*Correction Item*	5.2
4	Equipment changes	*Base case item*	4.2

It shows us that the greatest uncertainty at this point is related to changes and decisions expected to happen during design and construction.

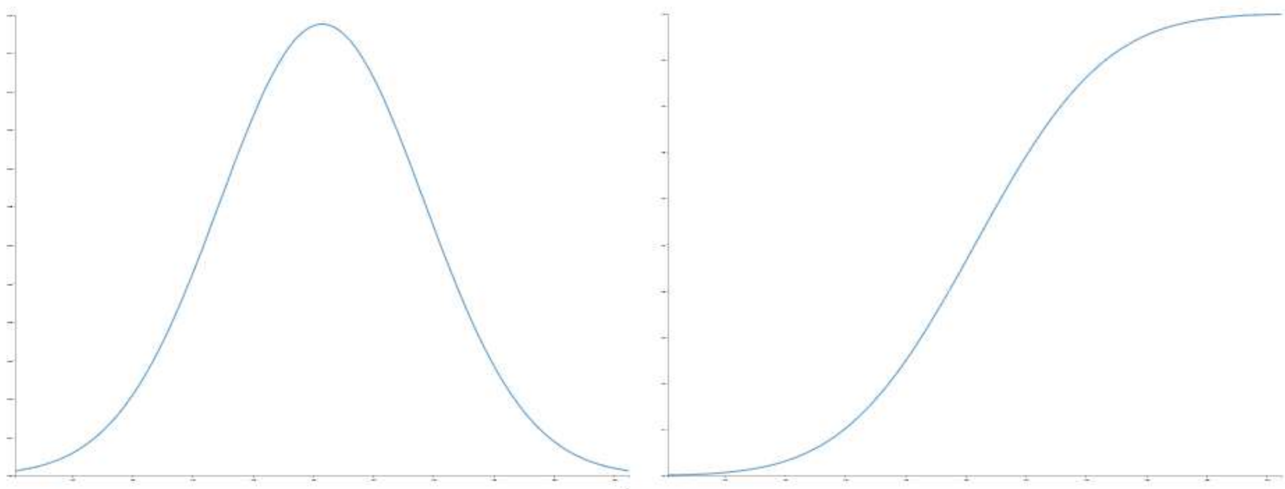
The action plan going forward may be as simple as sitting down with the Tuvaluan Navy and the designers, and trying to discuss, foresee, and limit all possible changes that might happen after the design and construction has begun. While this may seem obvious, being able to quantify and present the large influence that changes have on the uncertainty of the final weight may help to convince stakeholders of the need to minimize changes.

Presenting the Results

The mean value and standard deviations are often presented in the form of a normal distribution curve or a cumulative normal distribution curve [4].

These normal distribution graphs make it possible to see the probability of being within a lower and upper range of values. The cumulative normal distribution curve displays probability within a certain confidence limit (in this example, 90 % certain of outcome to be below a value).

There are almost endless materials available in the literature on the normal distribution curve, and the details of this will not be discussed in this paper.



Conclusion

The Successive Principle is an approach to handle uncertainty that should be explored further in areas beyond the typical economics and scheduling studies, and weight estimation seems to be a subject that is well-suited to the theory and approach.

References

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