IEEE Systems Journal, Volume 14, Issue 1, 2019, pp. 1257 - 1264
DOI: 10.1109/JSYST.2019.2923360

A Method to Establish a Trade-Space of System Requirements and Life Cycle Cost

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***Abstract*—Systems engineering traditionally approaches design of systems through determination of requirements for and implementation of a system. The system is conceived as something to enable achievement of an effect with the tacit assumption that the system to be designed must achieve technical performance, including availability characteristics, which enable delivery of the whole of the intended effect. This approach determines the technical requirements of the system to ensure achievement of the system purpose under assumptions about how the system, or fleet, would be deployed to provide the intended service. Commonly cost is addressed after requirements, either to find the cheapest method to achieve the requirements or as one dimension of a trade-space analysis. We explore a different philosophy for finding the system requirements; starting with the required system level service provision, but agnostic about the technical quality needed. We investigate a trade-space including the life cycle cost (LCC) of service provision as a contribution to determining subsystem requirements. We model the life cycle, for many variations of technical composition, using a Monte Carlo method, and show that a trade-space of LCC and requirements is likely to produce a cheaper solution than starting with sub-system requirements.**

***Index Terms*—Costs, System lifecycle management, Systems design, Systems requirements management, Systems technical assessment**

I. Introduction

THIS paper explores a concept which follows from approaching systems engineering with a focus on conceptualizing the system as means to achieve a defined effect. This concept is stated in classical textbooks on systems engineering [1]. However, the conventional pathway of projects is to address the system level requirements with assumptions about the method by which these systems level requirements will be met. The assumptions include factors such as the fleet size, the number of instances of the system to be built in order to provide a required number in active service with a particular availability, or that an extended service life will be provided by the original samples of the system manufactured rather than by a replacement series of instances. The impact of these assumptions is a demand for a quality standard in the system which will sustain deployment of the same instances of the system for a duration that is technically very difficult to achieve.

This concern brings us to face a continuing pressure in system development, the concern for budget [2]. There are several aspects of the concern about budget: the growing size and sophistication of systems, particularly with expensive characteristics such as deeply embedded networking with other systems, increases the real value of systems at a rapid rate. An example was Augustine's 1980 prediction that the US defense budget could afford one plane, not one kind of plane, in 2053, based on the historic cost escalation [3]. The competition for funding between potential system developments, which manifests in the government sector as the budget allocation to each of competing policy objectives, and in the private sector as the need for demonstrated return on investment, results in desire for more accurate prediction of project costs, and minimization of those costs, in the early phases of project consideration and development.

The cost related factors associated with systems projects lead to the conclusion that cost, and return on investment for business enabling systems, are an important dimension of evaluation of all projects. The system performance itself can only be described in terms of multiple measures of aspects of performance, and so requires multiple dimension of measure to describe [4]. The measures of dimensions of performance collectively describe what service the system is capable of providing. These measures could be used to determine achievable performance goals such as amount of work done and the availability of success delivering that work. It is normal to perform a trade study of these measures of performance to guide selection of a particular design proposal. For most systems there is a threshold level of performance for which the system would be 'satisfactory' and performance beyond that threshold may be valued according to a 'value for scale' function.

The initial investment to acquire a system is often a small proportion of the total life cycle cost (LCC) and consumables, maintenance and other operating costs are major parts of the total LCC [1][2]. We also observe that in many technologies the

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Manuscript received XXX/XXX/XXXX. This work was supported by Nadirah's PhD scholarship – Lectureship Program of International Islamic University Malaysia.

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cost of improving quality, particularly as represented by non-performance requirements, such as mean time to failure (MTTF) and mean time to repair (MTTR), increases faster than a linear relation with quality improvement. This effect is common in purchase of products and systems in both personal and professional contexts.

The financial dimension of the system is generally treated separately because the finance is the means of enabling the delivery of the 'in the world' capability enabled by the system. Two approaches can be taken to the financial dimension: it could be treated as directly tradeable with the system performance metrics, or it could be treated separately, with the final proposal selection being either the cheapest proposal that satisfies the performance threshold or the proposal which provides the greatest 'value' given the value for scale in excess of the threshold. The choice of approach depends on both the scenario and the approach of the decision making stakeholder.

Our line of reasoning, following Palmer [5], who used the tradition of continental philosophy that built upon Heidegger [6], is that the system under development must enable a capability, the ability of the user to bring effects in the world, as an instrument of the user's intent. This perspective is also foundational to the work of Floyd [7]. The user's concern is to have means to effect their intent, and would like to achieve this outcome at the lowest expenditure of resources possible.

A further factor which contributes to the current assumption set, referred to in the first paragraph, is the systems thinking issue of 'systems boundary'. This issue, and means to engage with it to formulate concepts for projects and deliverables which will enable effective interventions, was foundational to the work of Checkland [8][9]. The challenge of systems boundary in systems engineering arises, in part, because of the division of action across organizational boundaries with relationships that include contractually binding descriptions of what is to be delivered, which is usually described as a thing that the contractor will deliver which the principal in the contract believes will enable their purpose, rather than as means to achieve a defined effect in the world. The effect of this is that implementation of the ideas in this paper may require a change to the description of the subject matter of systems development contracts.

Our approach differs from existing methods to address the combination of cost, performance and availability of systems under development. The conceptualization of the system as means to produce an effect allows the provision to be distributed variously across one item or a fleet of assets which together provide the required performance and availability.

The non-linear relationships of quality and achieved performance, suggest value in exploring the concept of a trade-space including the technical requirements to be achieved by a system and the LCC against variations of the sub-system elements. Further, an intuitive view of the relative cost of the alternatives is probably wrong because of the impact of factors which need analysis [10]. This paper reports a quantitative exploration of the properties of our trade-space of technical requirements related to reliability, maintainability, and LCC with the purpose of determining whether there is enough *prima facie* evidence of value of the concept to show that it is worthwhile pursuing this concept.

II. Background Theory

The acquisition and through life support costs of systems are increasing providing continuing pressure for cost minimization [11]. We follow Fabrycky and Blanchard [2] in using the system life cycle as the foundation for system value and cost analysis. However, their approach constrains analysis to particular design proposals, with emphasis on the whole life cycle. There are many books about engineering economics but Fabrycky and Blanchard is the only one that frames discussion from the system LCC perspective rather than the elements of the analysis. However, their work does not develop as a core approach LCC analysis as an element in a trade-space analysis with technical requirements.

Two of the commonly accepted economic measures used in LCC analysis are Net Present Value, NPV, and Internal Rate of Return, IRR. NPV is calculated using equation (1).

$$NPV = \sum_{j=0}^{n} \frac{F_j}{(1+i)^j} \qquad (1)$$

Where F_j is the cash flow in year j of the life cycle, i is the interest rate used for the analysis, and the life cycle has a total of n years.

IRR is defined as the interest rate, i, for which $NPV = 0$.

NPV is a measure which compares proposals based on absolute project value whilst IRR compares proposals on the basis of the rate of return. Consequently, NPV is effective for comparing proposals of similar value whereas IRR is effective in comparing proposals of significantly different value [12].

The choice between NPV and IRR, and the required threshold value of IRR, is made by organizational policy rather than the manager of a particular project.

A trade-space is the space spanned by the set of possible design options [13], usually described at a higher level of decision between fundamentally different approaches to system design, for example [14], rather than as a guide to detail design decisions, such as we explore. The higher level analysis to distinguish fundamentally different approaches to a project corresponds to the high level strategic analysis to determine the feasibility and desirability of a broad architectural approach, as described in [3]. We have applied our method to the lower level of choosing between design alternatives within an overarching architecture family which would be explored once the higher level decision had been made. The challenge presented in selection of the most desirable design proposal is that each design proposal offered provides particular measures of achievement in a list of distinct dimensions [4]. The description of the expected achievement of each proposal requires the same number of measured dimensions [4]. The multidimensionality presents a challenge when the decision maker needs to resolve which of the proposals is "best". This challenge is normally resolved using multi-criteria trade-space analysis methods.

Trade-space analysis is the formalized process of determining the “best” proposal in this multi-dimensional situation. There are various methods used, but most methods share the activities of identifying the important dimensions, the relative importance weighting of each, the measure of predicted achievement in the dimension, and a value for scale function. These factors are combined to produce a score for each design alternative, enabling ranking of the alternatives and selection of the preferred alternative.

LCC can be included as a dimension of the trade-space. This has three disadvantages that have prompted this work:

1. The value for scale functions for all dimensions, with cost included, may lead to compromises on achievable performance caused by an undue, but hidden influence of the cost dimension;
2. The value for scale function in the cost dimension is based on an *a priori* expectation of what cost is realistic rather than looking for the best cost that achieves the required system performance;
3. The cost dimension is treated as directly equivalent to all other dimensions which could obscure the fact that the engineering must develop an appropriate solution to the need.

In trade-space analysis it may be possible to identify *a priori* some proposals as dominated by others, thereby reducing the analysis needed. In other cases it is impossible to make such an *a* priori judgment, resulting in need for a full analysis. We performed a full trade-space analysis because our work was focused on exploring the nature of the trade-space, and one of our conclusions is that there is no *a priori* basis for determining dominated alternatives in a trade-space involving the LCC implications of choices about the quality of subsystems.

Dwyer *et al* [10] sought a metric of complexity to inform decisions about the cost impact of high architectural decisions but not at the level of detail alternatives. Sease *et al* [15] modelled the stakeholder value of solutions. Their approach is unsuitable for detail distinction between alternatives.

Our approach, superficially, appears to be a combinational design approach, because we analyze all the cases not ruled out as infeasible or impermissible for other reasons, such as non-achievement of threshold performance. Albarello and Welcomme [16] defend an exhaustive approach as ensuring the solution is not biased by the designer’s experience. Kim *et al* [17] describe a combinatorial approach to selection of parts from a catalog to find the lowest cost means of meeting the technical requirements. They use genetic algorithms to navigate the space. This differs from our method. We begin with the set of alternative which have been determined to be feasible and permissible, and then seek the LCC preferred solution. Hoshino and Ota [18][19] describe a combinatorial design method to select a single kind of equipment item from a set of alternatives.

III. METHODOLOGY

A. Analysis Model Construction

We performed a study of a hypothetical system comprising a set of sub-systems in series connection with most of the subsystems multiplied in either a 2- or 3-parallel redundant configuration, in the structure in Fig 1. Therefore, at the architecture level, as addressed by Crawley *et al* [3], we have two levels of redundancy as one factor which will be tested by our method. The system structure followed the arrangement of a satellite communications system, with a set of ground station subsystems connected in series but, to enhance system reliability, are connected in parallel sets for each subsystem. In Fig 1 the set of elements A ... J on each side of the satellite, K, represent two base stations used in a bi-directional commercial setting. We chose to analyze a system structured like a satellite communications system to provide a tangible structure, but in the absence of cost and reliability data for the elements our results are not a contribution to satellite system design, but rather are an exploration of the potential for the trade-space concept we described above.

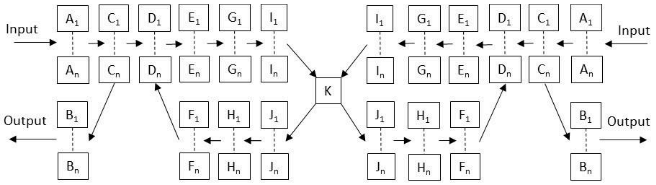

Fig 1. System structure configuration for our hypothetical system under test.

In Fig 1 we show an architecture with parallel redundancy, n instances of each subsystem, implemented as either 2 or 3, in a parallel cold-redundancy arrangement. Each system element was described by data attributes of:

1. Initial investment cost in dollars, a deterministic value.
2. Annual operation cost in dollars, a deterministic value.
3. Mean Time Before Failure, $MTBF = \frac{1}{\lambda}$, using the reliability function, $R(t)$, associated with the failure function, $F(t)$, using equation (2).
$$R(t) = 1 - F(t) = \int_t^\infty f(t)dt \tag{2}$$
We assume the failure function is Gaussian in the absence of a basis to use a different distribution. This data is fundamentally stochastic.
4. Time to repair, following a failure. The duration of loss of service of a system element depends on the time it takes to perform all the activities between the failure and restoration of the element. We used a three step function representing a first site visit repair, an intermediate duration requiring greater work and inputs, and an extended repair involving supplier work. This follows the field, base and supplier maintenance framework. This is a stochastic data item.
5. Cost of repair. The cost of repair is linked directly to the time of repair distribution, with a cost for each of field, base and supplier maintenance work.
6. Each subsystem type has its own set of data items for each of these attributes for each of five $MBTF$ values. We used the five values of $MTBF$: 0.5, 2.5, 3.7, 4.5 and 5 years.

In our model we assumed all alternatives considered could provide at least threshold satisfactory performance, when operating correctly. Effectively, we assumed no additional value for providing better than threshold performance, making the problem one of finding the lowest LCC configuration. If the system value were related to the achieved performance, after the analysis we describe to produce Table VI, a further trade of LCC and value of achieved performance would be required. Alternatively, if the different performance can be linked to financial value of the system, that value could be incorporated into this analysis.

B. *Data for the Model*

A challenge in this kind of research is the difficulty for an 'outsider' to obtain truly realistic (not exact) cost data from vendors because they do not offer business-to-business pricing with openly available pricelists, rather only discussing pricing as part of negotiation of a potential sale.

A possible way to overcome this problem would be to get data from an industry participant but this has the challenges of existence of relevant information and the business sensitivity of cost data.

To proceed we made the following assumptions.

1. The initial cost of equipment follows an increasing cost for scale as $MTBF$ increases. This follows the common observation that improvement in quality costs more as quality improves. This relationship is shown in Fig 2.
2. Annual operation cost varies only a small amount as 'quality' changes, and the relationship is not systematic.
3. The failure function follows a Gaussian distribution.
4. Time to repair follows the form of Fig 3.
5. Cost of repair follows the form of Fig 4. The probability of each step of the time and cost to repair functions is the same in both Fig 3 and Fig 4.

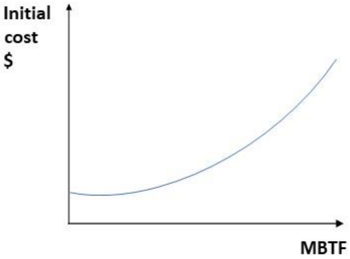

Fig 2. Initial cost for scale relationship.

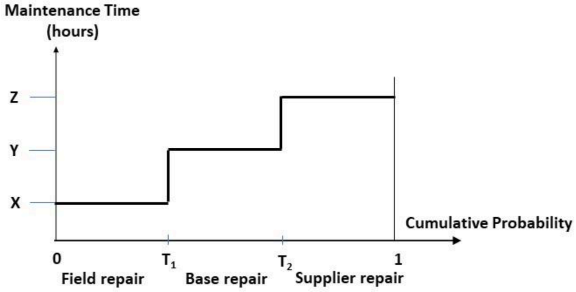

Fig 3. Maintenance time distribution function assumed in modelling.

C. *Modelling Method*

The data has two forms, deterministic and stochastic. The stochastic data points to Monte Carlo methods for analysis. To find the LCC distribution for each proposal we performed a Monte Carlo analysis of one million lifecycles of 20 years, to find the time of failures, time to repair and cost to repair, and thus the time and amount of expenses based on random number functions that determined the actual time of failure and time and cost of repair in the models. The lifecycle model process was event driven, identifying the time of the next failure or the next return to availability. This process found the cash flow for each year of the lifecycle. We produced the annual cash flow and then LCC for each lifecycle.

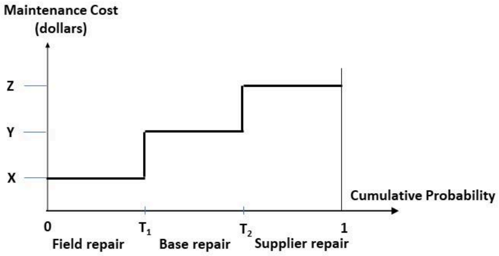

Fig 4. Maintenance cost distribution function assumed in modelling.

We transformed annualized cash flow to LCC using Net Present Value, NPV, for each of three interest rates: 5%, 10% and 20%, chosen as rates representative of different types of commercial or industrial cost analysis. We plotted the NPV distributions for each design configuration and for each NPV and observed the distributions approximated normal distributions, with higher interest rates associated with lower mean values and higher standard deviation.

Our first modelling analysis compared configurations in which all the subsystem types, $A \dots J$, had the same $MBTF$, with either two or three parallel redundant sets of elements. Then we performed analyses in which we began with all subsystems with $MBTF = 5\,years$ and substituted, systematically, to analyze all possible combinations, one, two, three, etc … subsystem types at a time at $MBTF = 0.5\,years$ to find the mean expected LCC.

Table I shows the data we used in our modelling. In the next section we report results of these analyses.

IV. RESULTS

In this section we present, in detail, some of the results of our modelling analysis, an explanation of the full set of modelling we performed and a table which summarizes the results.

A. *Initial Set of Modelling Results*

First we modelled the effect of all the subsystems, $A \dots J$, set to the same $MBTF$ value for each of the 2-parallel and 3-parallel configurations. This produced the results for NPV, and rank order of the preference for design alternatives presented in Tables II and III.

TABLE I

DATA DESCRIBING THE SUBSYSTEMS ELEMENTS SHOWN IN THE SYSTEM ARCHITECTURE OF FIGURE 1

Descriptive Title	High Reliability, High Cost																Low Reliability, Low Cost			
Item	$\lambda = 5\ years$				$\lambda = 4.5\ years$				$\lambda = 3.7\ years$				$\lambda = 2.5\ years$				$\lambda = 0.5\ years$			
Initial investment	$2.5 million				$2.425 million				$2.35 million				$2.275 million				$2.20 million			
Annual operation cost	$45k				$48.75k				$52.5k				$56.25k				$60k			
Subsystem	Initial Cost	0-T_1 T_1=.2	T_1-T_2 T_2=.5	T_2-1	Initial Cost	0-T_1 T_1=.2	T_1-T_2 T_2=.5	T_2-1	Initial Cost	0-T_1 T_1=.1	T_1-T_2 T_2=.4	T_2-1	Initial Cost	0-T_1 T_1=.2	T_1-T_2 T_2=.5	T_2-1	Initial Cost	0-T_1 T_1=.1	T_1-T_2 T_2=.4	T_2-1
A	$1.8M	8hr/$2k	40hr/$15k	900hr/$600k	$1.475M	8.5hr/$7.5k	42.5hr $15.5k	1175h $512.5k	$1.15M	11hr/$2.15k	45hr/$16k	1450h $425k	$0.825M	9.5hr/$2.225k	47.5hr $16.5k	1725h $337.5k	$0.5M	10hr/$2.3k	50hr/$17k	2000h $250k
B	$1.8M	10hr/$2k	40hr/$15k	900hr/$600k	$1.475M	11hr/$2.075k	48.75 $15.5k	1175h $512.5k	$1.15M	11hr/$2.15k	52.5hr $16k	1450h $425k	$0.825M	12hr/$2.225k	52.5hr $16.5k	1725h $337.5k	$0.5M	14hr/$2.3k	60hr/$17k	2000h $250k
C	$1.5M	8hr/$2.5k	40hr/$20k	900hr/$600k	$1.2625M	8.5hr/$2.475k	42.5hr $20.5k	1175h $512.5k	$1.025M	11hr/$2.45k	45hr/$21k	1450h $425k	$0.7875M	9.5hr/$2.425k	47.5hr $21.5k	1725h $337.5k	$0.55M	10hr/$2.4k	50hr/$22k	2000h $250k
D	$3M	8hr/$3k	40hr/$25k	900hr/$800k	$2.4M	8.5hr/$2.875k	42.5hr $25.75k	1175h $675k	$1.8M	11hr/$2.75k	45hr/$26.5k	1450h $550k	$1.2M	9.5hr/$2.625k	47.5hr $27.25k	1725h $425k	$0.6M	10hr/$2.5k	50hr/$28k	2000h $300k
E	$1.5M	8hr/$2.5k	40hr/$20k	900hr/$600k	$1.2625M	8.5hr/$2.475k	42.5hr $20.5k	1175h $512.5k	$1.025M	11hr/$2.45k	45hr/$21k	1450h $425k	$0.7875M	9.5hr/$2.425k	47.5hr $21.5k	1725h $337.5k	$0.55M	10hr/$2.4k	50hr/$22k	2000h $250k
F	$1.5M	10hr/$2.5k	40hr/$20k	900hr/$600k	$1.2625M	11hr/$2.475k	48.75 $20.5k	1175h $512.5k	$1.025M	11hr/$2.45k	52.5hr $21k	1450h $425k	$0.7875M	12hr/$2.425k	52.5hr $21.5k	1725h $337.5k	$0.55M	14hr/$2.4k	60hr/$22k	2000h $250k
G	$1.5M	8hr/$2.5k	40hr/$20k	900hr/$600k	$1.2625M	8.5hr/$2.475k	42.5hr $20.5k	1175h $512.5k	$1.025M	11hr/$2.45k	45hr/$21k	1450h $425k	$0.7875M	9.5hr/$2.425k	47.5hr $21.5k	1725h $337.5k	$0.55M	10hr/$2.4k	50hr/$22k	2000h $250k
H	$1.5M	10hr/$2.5k	40hr/$20k	900hr/$600k	$1.2625M	11hr/$2.475k	48.75 $20.5k	1175h $512.5k	$1.025M	11hr/$2.45k	52.5hr $21k	1450h $425k	$0.7875M	12hr/$2.45k	52.5hr $21.5k	1725h $337.5k	$0.55M	14hr/$2.4k	60hr/$22k	2000h $250k
I	$1.8M	8hr/$2k	40hr/$15k	900hr/$600k	$1.475M	8.5hr/$2.075k	42.5hr $15.5k	1175h $512.5k	$1.15M	11hr/$2.15k	45hr/$16k	1450h $425k	$0.825M	9.5hr/$2.225k	47.5hr $16.5k	1725h $337.5k	$0.5M	10hr/$2.3k	50hr/$17k	2000h $250k
J	$2.5M	10hr/$3k	40hr/$25k	900hr/$800k	$2.025M	11hr/$875k	48.75 $25.75k	1175h $675k	$1.55M	11hr/$2.75k	52.5hr $26.5k	1450h $550k	$1.075M	12hr/$2.625k	52.5hr $27.25k	1725h $425k	$0.6M	14hr/$2.5k	60hr/$28k	2000h $300k

In Table II we observe that the rank order of preference of the alternatives for interest rates 5% and 10% is the same, but differs for 20%. In contrast, in Table III the rank order of alternatives is the same for all three interest rates. This shows that the business evaluation measure, the choice of NPV interest rate could influence the design alternative choice. The basis for this effect is that the alternatives involve different amounts and timing of expenditure, making a lifecycle, time value of money, measure based rank ordering of alternatives potentially influenced by the interest rate used in the comparison.

TABLE II

MEAN NPV VALUES AND RANK ORDER OF ALTERNATIVES FOR DESIGN ALTERNATIVES WITH ALL SUBSYSTEMS WITH THE SAME $MBTF$ FOR EACH OF THREE NPV INTEREST RATES FOR THE 2-PARALLEL ARCHITECTURE

$MBTF$	0.5 years	2.5 years	3.7 years	4.5 years	5 years
NPV rate	Rank Order and NPV mean				
5%	3 $102M	1 $308M	5 $73.8M	2 $150M	4 $99.6M
10%	3 $2.02M	1 $141M	5 -$25M	2 $28.4M	4 -$19.2M
20%	3 -$90.1M	1 -$13.6M	4 $116M	2 -$83.4M	5 -$121M

TABLE III

MEAN NPV VALUES AND RANK ORDER OF ALTERNATIVES FOR DESIGN ALTERNATIVES WITH ALL SUBSYSTEMS WITH THE SAME $MBTF$ FOR EACH OF THREE NPV INTEREST RATES FOR THE 3-PARALLEL ARCHITECTURE

$MBTF$	0.5 years	2.5 years	3.7 years	4.5 years	5 years
NPV rate	Rank Order and NPV mean				
5%	4 $109M	1 $336M	3 $165M	2 $306M	5 $58.8
10%	4 $5.15M	1 $157M	3 -$37M	2 $131M	5 -$41.5M
20%	4 -$90.6M	1 -$60.3M	3 $80.8M	2 -$79.7M	5 -$134M

B. Mixed Quality Subsystems Results

In our next set of modelling we hypothesized that there may be a LCC advantage to be gained through substitution of one of the subsystem types from the best available kind, $MBTF = 5\ years$, to the lowest quality kind available, $MBTF = 0.5\ years$. We performed this analysis by systematically working through each subsystem type in the system architecture to find the LCC effect. We show the results of this analysis in Table IV and Table V for 2-parallel and 3-parallel alternatives respectively.

In contrast to the results in Tables II and III, where the changes all involved cheaper up-front cost and poorer reliability of all subsystems, resulting in more frequent corrective maintenance events, Tables IV and V show the effect of subtler changes to the system alternatives, and a greater plurality of available alternatives. One effect of this change is that, whereas in Tables II and III there were only a few rank order changes resulting from interest rates, in Tables IV and V there is much more change of rank order associated with interest rates. This observation is important in our argument that it is useful to build a trade-space including the reliability and maintainability requirements of potential subsystems and the system LCC to obtain the cheapest means to provide the required performance.

We continued to substitute $MBTF = 0.5\,years$ subsystems in all possible combinations of two-at-a-time, to nine-at-a-time, in alternatives where the remaining subsystems all have $MBTF = 5\,years$. Full results are available in the PhD thesis of Abdul Rahim [20].

TABLE IV

MEAN NPV VALUES AND RANK ORDER OF ALTERNATIVES FOR DESIGN ALTERNATIVES WITH ONE SUBSYSTEM TYPE AT A TIME SUBSTITUTING THE *MTBF=0.5 YEARS* VERSION. ALL OTHER SUBSYSTEMS HAVE *MTBF=5 YEARS* FOR EACH OF THREE NPV INTEREST RATES FOR THE 2-PARALLEL ARCHITECTURE

Subsystem type substitution	All *MBTF=5 years*	A	B	C	D	E	F	G	H	I	J
NPV rate	Rank Order and NPV mean										
5%	7 $80.4M	3 $109M	4 $97.8M	11 $59.7M	5 $95.1M	1 $153M	8 $76M	2 $119M	9 $72.6M	10 $71.6M	6 $93M
10%	6 -$19.2M	5 -$60.9M	3 -$13.5M	11 -$61.9M	4 -$14.3M	2 $23.7M	7 -$28.7M	1 $26.1M	8 -$31.1M	9 -$31.4M	5 -$16.2M
20%	6 -$121M	5 -$143M	4 -$116M	9 -$132M	3 -$115M	1 -$95.4M	7 -$125M	2 -$104M	8 -$127M	7 -$125M	5 -$117M

TABLE V

MEAN NPV VALUES AND RANK ORDER OF ALTERNATIVES FOR DESIGN ALTERNATIVES WITH ONE SUBSYSTEM TYPE AT A TIME SUBSTITUTING THE *MTBF=0.5 YEARS* VERSION. ALL OTHER SUBSYSTEMS HAVE *MTBF=5 YEARS* FOR EACH OF THREE NPV INTEREST RATES FOR THE 3-PARALLEL ARCHITECTURE

Subsystem type substitution	All *MBTF=5 years*	A	B	C	D	E	F	G	H	I	J
NPV rate	Rank Order and NPV mean										
5%	6 $58.8M	8 $55.8M	1 $114M	2 $105M	5 $85M	10 $40.1M	7 $56M	9 $52.4M	4 $91.4M	3 $104M	11 $35M
10%	7 -$41.5M	10 -$43.5M	1 -$2.3M	2 -$9.1M	5 -$21M	11 -$53.3M	8 -$42M	9 -$42.6M	4 -$18.2M	3 -$9.3M	6 -$35M
20%	5 -$134M	7 -$136M	2 -$110M	3 -$114M	4 -$119M	8 -$139M	1 -$105M	6 -$135M	4 -$119M	3 -$114M	9 -$140M

C. Summarization of Results

The final stage of result presentation is a table showing the highest 50 alternatives in rank order of NPV, for one interest rate. Table VI shows the rank order of mean NPV results for each alternative modelled. We observe that in Table VI there is no systematic relationship of alternative and LCC rank order. We also observe a mix of 2 and 3 values in the "parallel redundancy" column of Table VI, indicating that there was no bias to provide a clear choice of one redundancy architecture over the other, showing that this method can contribute to decision making at both architectural and specific design levels, and that the cost distributions for different architectures may overlap, making neither dominated by the other. This shows that there is no way that the preferred design proposal characteristics could be determined in advance of full LCC analysis. This result also shows that it is not possible to construct a trade-space that could be investigated using a genetic algorithm approach following Kim *et al* [17].

Therefore, in systems which provide defined service but offer opportunity for alternative combinations of initial investment, reliability, and maintenance and support costs, the cheapest solution cannot be predicted using an *a priori* rule, such as "use the best quality components", nor "use the cheapest", etc.

V. CONCLUSIONS

We began by seeking means to design systems to produce solutions, providing required performance for the lowest LCC. We use LCC because it avoids the distortions arising from analysis based on only a part of the lifecycle.

Our approach recognizes stakeholders acquire systems to achieve effects in the world. This recognition leads to our use of a simple threshold performance level approach, but if there is a financial value for scale function that function would inform the LCC calculation. Our approach is an initial exploration simplification of our approach.

The standard doctrine of systems engineering demands a system is designed as means to generate the intended effect without prejudicing the design with any solution idea. A choice to demand that subsystems have particular reliability, as the means of providing the desired system availability, rather than focusing on the system level property and permit various approaches which achieve the desired result as permissible could result in a design with higher LCC than necessary.

We have shown that if an analysis is performed at the subsystem level of the LCC impact of differences in the quality of subsystems, that overall system LCC for a system which provides at least a threshold performance capability, the configuration of the system, including the choices for each of the competing choices is not a priori predictable. This observation shows value in pursuing research of the kind presented in this paper to find better methods for performing this type of analysis and to develop understanding of the properties of this approach. We also observed that the trade-space may be beneficially augmented with cases which represent different architecture choices, in our case the number of parallel instances of elements, again without an *a priori* predictable result.

TABLE VI
RANK ORDER OF ALL ALTERNATIVES ANALYZED FOR NPV INTEREST RATE OF 5% (FIRST 50 ROWS ONLY)

Rank	Parallel redundancy	NPV	Subsystems at $MBTF = 0.5\ years$ (or other notes
1	3	\$336M	All subsystems MTBF= 2.5 years
2	2	\$308M	All subsystems MTBF= 2.5 years
3	3	\$306M	All subsystems MTBF= 4.5 years
4	2	\$256.2M	B, D, G, H
5	2	\$253.7M	A, B, D, E, G, J
6	3	\$243.3M	B, D, F, I
7	3	\$240.8M	B, C, D, F, H
8	2	\$235.8M	B, D, E, H
9	3	\$231M	B, D
10	2	\$230.7M	A, B, D, E, G
11	2	\$222.6M	B, D, E, G, H
12	2	\$210.7M	B, D, E, G, J
13	3	\$210M	F, I
14	2	\$176M	A, B
15	3	\$171.8M	F, H
16	3	\$165M	All subsystems MTBF= 3.7 years
17	2	\$161M	A, G, J
18	3	\$156.6M	B, D, F, H
19	2	\$153M	E
20	3	\$152.3M	F, H, I
21	2	\$150.4M	D, E, H
22	2	\$150M	All subsystems MTBF= 4.5 years
23	2	\$150M	B, D, G, J
24	3	\$146M	D, H
25	2	\$140M	B, D, E
26	3	\$139M	B, D, I
27	2	\$137M	A, B, G
28	2	\$137M	A, B, D
29	2	\$135M	A, J
30	3	\$135M	B, C, D, H, I
31	2	\$133M	B, J
32	2	\$133M	B, D, E, J
33	2	\$131M	B, E, G
34	2	\$130.2M	B, D, H, J
35	3	\$130M	B, I
36	2	\$129M	D, G, J
37	2	\$127M	B, D
38	3	\$126M	B, D, H, I
39	2	\$125M	A, B, D, E
40	3	\$125M	B, C, D, I
41	2	\$124.2M	B, E, H
42	2	\$122M	A, B, J
43	2	\$122M	A, B, D, G
44	2	\$122M	A, B, G, J
45	2	\$120.4M	B, G, H, J
46	2	\$119M	G
47	2	\$119M	D, E
48	2	\$118.7M	B, D, E, G, H, J
49	2	\$115M	B, E
50	3	\$114M	B

The observations, that both the system architecture, and the system design within an architectural concept, could be impacted by this approach indicate the value in a system acquirer performing this kind of analysis before Call for Tender documentation is developed, and for the producing organization to apply the method in the specific design, which in turn would require the acquiring organization to provide whole of life cost structure information to the producer to provide a foundation for this level of design implementation. Alternatively, the kind of analysis presented here could be implemented by changes in the responsibilities of the parties to a bespoke development acquisition contract to better incorporate the project impacts of this method.

Another application of this work which will require additional research is the development of requirements for systems and their subsystems developed as means to provide services for sale, or for optimizing LCC of systems sold for commercial purposes, where differential pricing could be introduced for different qualities of service guaranteed to purchasers of the service.

We recognize, as we experienced, the difficulty in obtaining pricing from suppliers before negotiating specific supply agreements. Alternatively, if the subsystems will be bespoke developments both the technical performance, reliability and maintainability, and the LCC data will all be estimates, requiring methods to incorporate the effect of the error bounds on the results. It will also be useful to investigate the application of this approach as a tool during project performance, in order to incorporate evaluation of the current status of the project and the impact of choices available at any stage at any time during the project, or even through the system life-cycle, and with the capacity to incorporate the data obtained to date.

We conclude, future research to refine the processes described in this paper is warranted. In addition, this paper suggests that there would be value in further developing the techniques to create a trade-space of technical requirements, related to both performance and quality characteristics of the system, and the total value provided by the system through its life cycle, in addition to the LCC of the system.

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