# A DIGITAL DECISION MAKING FRAMEWORK INTEGRATING DESIGN ATTRIBUTES, KNOWLEDGE AND UNCERTAINTY IN AEROSPACE SECTOR

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## ABSTRACT

The delivery of integrated product and service solutions is growing in the aerospace industry, driven by the potential of increasing profits. Such solutions require a life cycle view at the design phase in order to support the delivery of the equipment. The influence of uncertainty associated with design for services is increasingly a challenge due to information and knowledge constraints. There is a lack of frameworks that aim to define and quantify relationship between information and knowledge with uncertainty. Driven by this gap this paper presents a framework to illustrate the link between uncertainty and knowledge within the design context for services in the aerospace industry. The paper combines industrial interaction and literature review to initially define (1) the design attributes, (2) the associated knowledge requirements, and (3) uncertainties experienced. The concepts and inter-linkages are developed with the intention of developing a software prototype. Future recommendations are also included.

## KEYWORDS

Knowledge, design, uncertainty, digital feedback, life cycle.

## 1. INTRODUCTION

The aerospace industry is experiencing a shift from ad-hoc service provision to integrated product and service solutions that enable the delivery of the availability and capability required from an engine (Alonso-Rasgado and Thompson, 2006). This has promoted an emphasis of the life cycle implications of engine design due to the shift in the business model, which incentivises reduced maintenance cost whilst enhancing equipment operability/ functionality (Datta and Roy, 2009). The need to predict service requirements much earlier than the traditional model (e.g. spares sales) and the bundled nature of service delivery has increased the uncertainties experienced by the Original Equipment Manufacturer (OEM) (Erkoyuncu et al, 2009). As a result, the OEMs are facing challenges associated with the boundaries of their knowledge in delivering services within the emerging business model.

Knowledge can be defined in terms of a justified true belief (Nonaka, 1994). It involves personalised information, which is processed in the minds of individuals (Alavi and Leidner, 2001). In an industrial setting, knowledge is considered as an *'actionable understanding'*. Knowledge has typically been classified into tacit and explicit knowledge and the associated contents depend on the context. Tacit knowledge refers to the personal and experienced based nature of knowledge (Sobodu, 2002). On the other hand, explicit knowledge involves formally documented, systematic, and well structured language (Nonaka, 1994). Knowledge within the context of life cycle design includes a number of aspects associated to the different phases of an aero-engine (Doultsinou, 2010). The existence of knowledge enhances the confidence in events that have been predicted.

Uncertainty refers to things that are not known or known imprecisely (Walker et al, 2003). The sources of uncertainty have often been classified into two bases, including epistemic and aleatory (Erkoyuncu et al, 2010). Aleatory uncertainty refers to the uncertainty that arises from natural, unpredictable variation in the performance of the system under study (Daneshkhah, 2004). On the other hand, epistemic uncertainty arises from lack of knowledge about the behaviour of the system that is conceptually resolvable (Thunnissen, 2005). It is worth recognising that uncertainty does not have to hold negative consequences, it may also lead to positive outcomes. Though, it may have a constraining role from a decision-making perspective when designing an engine.

The link between knowledge and uncertainty has often been highlighted (in the case of epistemic uncertainty). Ackoff (1989) presents that with increased knowledge the level of uncertainty diminishes, though no mechanism has been proposed in literature that shows the relationship between knowledge and uncertainty in a qualitative or quantitative manner. To understand this relationship will further enhance decision making during the design process. For instance, it will be possible to conduct cost-benefit analysis to understand the value of changing the level of knowledge.

In light of the challenge of achieving optimised engine design, this paper aims to develop a framework/methodology: (1) to demonstrate the influence of knowledge on uncertainty, and (2) to visualise the implications of changing the level of knowledge on the level of uncertainty experienced in life cycle design. The objectives include:

- Capture the required areas of knowledge;
- Define a mechanism to capture the required value of knowledge;
- Identify a mechanism to capture the current state of knowledge;
- Develop a mechanism to change the knowledge level whilst representing the benefit; and
- Build a mechanism that links the level of knowledge and the level of uncertainty

Design attributes, knowledge and uncertainty in design are discussed in the following. A digital decision making framework based upon design attributes, knowledge and uncertainty is also presented along with discussion. This is followed by conclusions and future work.

## 2. DESIGN ATTRIBUTES

Within the context of this study, design attributes represent key features of customer requirements regarding aerospace-engine design architecture. Some of the key attributes include specific fuel consumption, weight, maintenance cost, and unit cost. Each design attribute should be considered as a source of value to the customer (increasing their revenue potential or reducing their costs). Whilst there are many design attribute level options to achieve product level requirements, analysing different options in a systematic and rapid manner is essential. Variation in options is driven by the performance against targets for each of the attributes, which may necessitate improving some design attributes and downgrading others. Thus, the manufacturer needs to devise measures (e.g. choose a design attribute value to change) to account for any difference between the current design attribute state and the customer-required level. Following are the key engine design attributes:

- *Specific Fuel Consumption (SFC)*: The weight flow rate of fuel required to produce a unit of power or thrust, for example, pounds per horsepower-hour;
- *Weight:* Whilst the granularity may vary (e.g. engine, component) it focuses on the weight in the product e.g. pounds;
- *Noise:* The total noise from all sources other than a particular one of interest (usually measured in decibels);
- *Unit cost:* The cost of a given unit of a product;
- *Life Cycle Cost (LCC):* A measurement of the total cost of using equipment over the entire time of service of the equipment; includes initial, operating, and maintenance costs;
- *Emission:* The substance discharged into the air, e.g. by internal combustion engine;

- *Development and testing cost:* Costs incurred during development and testing;
- *Thrust:* A propulsive force produced by fluid pressure or change of momentum of the fluid in a jet engine, rocket engine, etc; and
- *Reliability:* Consistent and productive engines, parts, etc.

Each design attribute will typically be assigned a minimum and maximum (or additional threshold) value agreed with the customer that guides the solution provider throughout the equipment life cycle. In achieving the requirements for each design attribute the solution provider may face a number of factors that influences its performance in achieving these targets. Additionally, the targets may change throughout the life cycle. The performance of the solution provider in reacting to and/or driving design attribute requirements throughout the equipment life cycle partly determines the satisfaction level of the customer and hence influences competitive positioning.

## 3. KNOWLEDGE IN DESIGN

For the purpose of this paper, knowledge is defined in the industrial setting as *'actionable understanding'*. A knowledge hierarchy (data-information-knowledge-wisdom) is defined, in which simple data could be enhanced up to information, knowledge and then wisdom level by increasing understanding and context independence. The authors contend that industrial value is only released when this hierarchy generates sufficient understanding to enable more effective or efficient decisions and actions to be taken.

For example, customer value from an aero-engine is released during the service phase of the product life cycle. Whilst functioning in service the engine contributes to the customer revenue generation (by supplying the motive power). In stark contrast, whilst out of operation for servicing the engine contributes only to costs. It is therefore a key requirement to understand the drivers of loss of function and maintenance requirements in order to achieve the maximum functional availability of the product. A knowledge of the maintenance drivers with availability of mitigation guidance for future designs or redesigns is clearly important and of significant value in this context.

Digital feedback of through-life engineering service knowledge to product design and manufacture is challenging. There is a lack of available structured methodologies for capturing and structuring service knowledge in order to map service knowledge onto design requirements. The challenge here is to devise an effective methodology to capture service knowledge gained from previous learning, possibly in a structured way, and then feedback to conceptual and detailed product design stages so that new/revised product designs incorporate the new learning.

Service knowledge is also important for the service/repair engineering functions of an organisation, especially for its uses in root cause analysis, problem solving, mitigation of operational risks, improving repair policies, recommendations of repair margins, etc. The knowledge of previous service experience could help reduce product life cycle cost by giving priority to mitigation of risks on those product commodities, which exhibit high costs. Keeping product life cycle cost at minimum is challenging.

The following feedback loops of through-life engineering service knowledge are considered in this paper: (1) service to design; and (2) manufacture/assembly to design. The design function has to understand both manufacture, assembly and operation and the challenge is to achieve a balanced design that minimises the design cost impact in all three stages (with appropriate weighting to their impact on customer value). In both cases, establishing effective feedback loop is also challenging.

The through-life engineering service knowledge and its impact on product design and manufacture is presented as a causal loop model (CLM) in Figure 1. The CLM is mapped across design, development and service stages of product life cycle. The design stage includes conceptual, preliminary and detailed product design. The development stage includes product engineering, manufacturing, assembly and testing. The service stage includes product service, repair and maintenance. Here links between causes and effects are represented across product life cycle stages that have positive or negative links representing increasing or decreasing effects of related causes. The CLM revolves around enhancing the service knowledge backbone (SKB) of an aerospace organisation, which could be partly achieved by improving service knowledge capture. The enhanced SKB could increase knowledge levels in conceptual and detailed product design stages, which could lead to optimise design characteristics. This could lead to increase confidence in previous design, design robustness, and decrease design costs and hence life cycle costs. Improved design characteristics could lead to improve design of fixtures, tooling and inspection and in effect the actual equipment. This could result in minimising maintenance burden, frequency of occurrence and operational disruption. As a result, the number of maintenance and repair events could be reduced with a commensurate reduction in cost of maintenance and repair leading to a reduction in life cycle cost. Quality could be improved by achieving an increased level of design robustness and together with decreased operational disruption it could result in improved customer service.

On other side, an increase in service knowledge capture will also result in higher costs of capturing and maintaining knowledge, hence increasing the life cycle cost. Variability in customer requirements is another factor that could lead to increase design costs, hence increasing the life cycle cost. A robust design may increase requirements of capabilities/skills, while higher confidence in design may reduce these requirements. Improved design of fixtures, tooling and inspection also increases these requirements, on provision of which the state of fixtures, tooling and inspection improves as well as quality. Provision of these requirements will result in higher life cycle costs in both cases. However, there is an optimum point at which the maximum value versus cost of enhancing service knowledge is achieved.

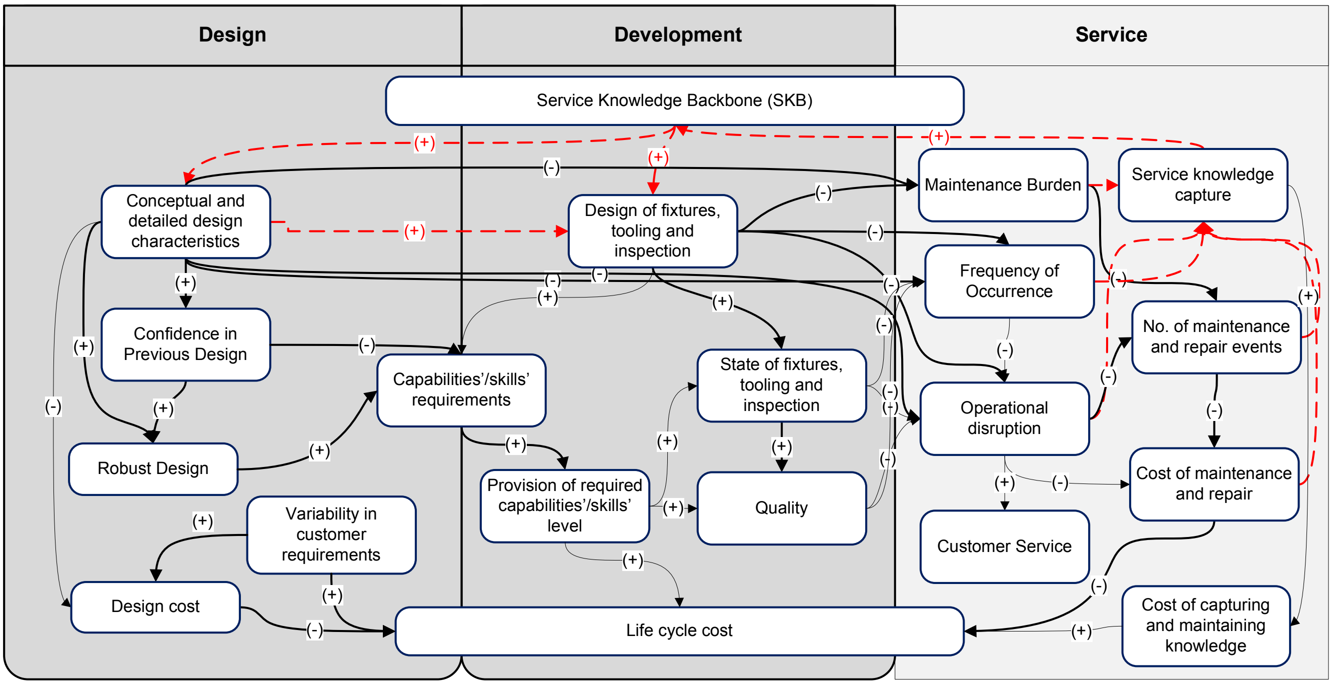


**Figure 1: Causal loop model: Through-life engineering service knowledge feedback to product design and manufacture**

## 4. UNCERTAINTY IN DESIGN

There are many types of uncertainties from a service perspective that can be experienced during the product design process. The sources vary driven by a number of factors and their degree of influence evolves over time. Major categories of uncertainties experienced in service delivery include:

- *Engineering uncertainty* considers factors that affect strategic decisions with regards to the future service and support requirements (i.e. how will the service be delivered? Offshore, obsolescence management, rate of system integration issues);
- *Operation uncertainty* considers factors that affect service and support delivery involved on a daily basis. It focuses on equipment level activities (i.e. how much service need will there be? Onshore, maintenance, quality of components and manufacturing, operating parameters);
- *Affordability uncertainty* considers the predictability in the customers ability to fund a project throughout its contractual duration (e.g. Customer ability to spend, customer willingness to spend);
- *Commercial uncertainty* considers factors that affect the contractual agreement, (e.g. exchange rates, interest rates, commodity and energy prices);
- *Performance uncertainty* considers factors that affect reaching the performance goals (e.g. key performance indicators); and
- *Training uncertainty* considers factors that affect the delivery of training to the customer.

The specified categories of uncertainties may have a strategic or operational influence over the design considerations. Along these lines, the affordability and commercial categories guide how the contract should be agreed at the outset from a financial perspective, whilst also taking account of relationships across the supply network. Industry and the customer jointly contribute the level of uncertainty experienced in these categories. On the other hand, the influence of the operation, engineering and training categories tend to be at an operational level on how service and support is to be delivered. It is also interesting to note the inter-linkages between each of these categories. For instance, with the delivery of training the uncertainty in the performance of the equipment reduces. This is mainly associated to the enhanced skill level to operate the equipment. A digital decision making framework is presented in the following section.

## 5. DESIGN ATTRIBUTES-KNOWLEDGE-UNCERTAINTY (DKU) FRAMEWORK

### 5.1. DKU FRAMEWORK PROPOSED

A digital decision making framework (DKU Framework) is proposed that links the role of design attributes, knowledge and uncertainty. The overall framework is presented in Figure 2. The DKU framework visualises specific relationships between the design attributes, knowledge and uncertainty in a map form. Industrial product-service system delivery is linked with design attributes, knowledge and uncertainty through outgoing knowledge adaptation and incoming service prediction capability (as shown in Figure 2).

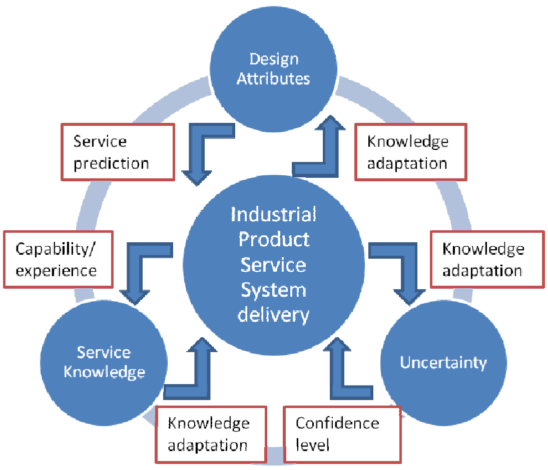


**Figure 2: DKU Framework**

CLMs are created and presented in the following to further elaborate on the DKU framework.

### 5.2. DKU FRAMEWORK DISCUSSION ON CAUSAL LOOP MODELS

A causal loop model (CLM) can represent causal effects of activities (Daneshkhah, 2004; Masood et al, 2011). This type of modelling helps identify aspects of complexities and dynamics can be modelled through this technique (Masood, 2009). Implementation of CLM has been reported in several case studies either standalone or as part of integrated approaches (Masood, 2009; Rashid et al, 2009; Zhen et al, 2009; Masood et al, 2010; Masood and Weston, 2011).

A CLM of the DKU Framework is presented in Figure 3, which looks into causes and effects related to an enhanced SKB. Here knowledge of nine (9) important design attributes are considered, which includes (as shown in columns): weight, SFC, noise, unit cost, LCC/maintenance cost, emission, development & testing cost, thrust and reliability/operational disruption. Desired design attribute trends are taken as initial conditions for this CLM i.e. lower weight, lower SFC, lower noise, lower unit cost, lower LCC/maintenance cost, lower emission, lower development & testing cost, higher thrust and lower operational disruption (higher reliability). Uncertainties are categorised into engineering, operation, affordability and commercial. *Engineering uncertainties* include rate of system integration issues, level of obsolescence, rate of rework, rate of capability upgrade, failure rate of software, maintaining design rights, cost estimating data reliability & quality, efficiency of engineering efforts, and cost of licensing and certification. *Operation uncertainties* include quality of components and manufacturing, component stress and load, operating parameters, maintainer performance, availability of maintenance support resources, effectiveness of maintenance policy part level, complexity of equipment, equipment utilisation rate, performance of internal logistics, supply chain logistics, rate of materials, sufficiency of spare parts, performance of suppliers' logistics, failure rate of hardware, location of maintenance, rate of beyond economical repair, turn around (repair) time, choice of fuel, mean time between failure data, no fault found rate, and rate of emergent work. *Affordability uncertainties* include customer ability to spend, customer willingness to spend, and project life cost. *Commercial uncertainties* include exchange rates, interest rates, commodity and energy prices, material cost, environmental impact, customer equipment usage, suitability of requirements, labour hour, labour rate, labour efficiency, clarity of customer requirements, and experience in other engine service provision.

The DKU-CLM presented in Figure 3 revolves around causes and effects of an enhanced SKB, which are mapped onto design attributes (in columns) and uncertainties (in rows). The CLM presents positive or negative effects of an enhanced SKB onto uncertainty types resulting in positive or negative effect on design attribute. Taking the reliability design attribute, it proposes that the effect of an enhanced SKB would be negative onto engineering uncertainty for reliability, which further results in higher reliability. It affects similarly on other uncertainties for reliability (operational, affordability and commercial) that are considered in this paper. It should be noted here that the paper discusses uncertainty types and their resultant effects; it does not go into detailed uncertainties, for which increasing or decreasing effect may be different. Thrust (another design attribute) has similar effects to reliability, which ends up in an increase with enhanced SKB while reducing respective uncertainties. The enhanced SKB affects respective uncertainties (engineering, operational, affordability and commercial) negatively for other design attributes (noise, weight, SFC, unit cost, LCC/maintenance cost, emission and development & training cost) resulting in negative effect on these design attributes.

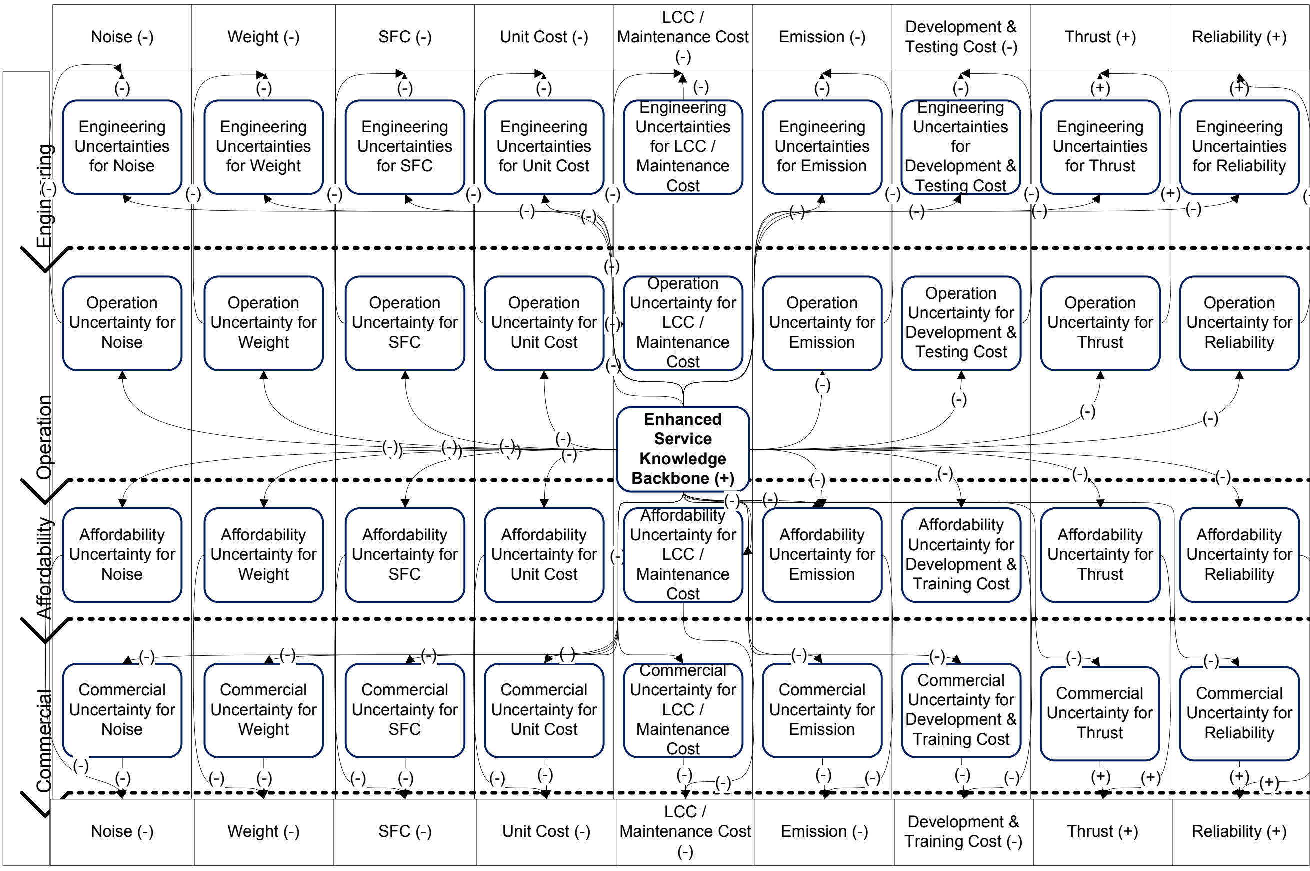


**Figure 3: DKU Causal Loop Model – SKB, Design attributes and Uncertainties**

Figure 4, through a causal loop model, demonstrate the link between knowledge and uncertainty within the context of "reliability". Further information about the content includes:

"Rate of system integration" refers to the combination of individual systems whether developed in house, outsourced or both. It typically forms a major responsibility of OEMs, whilst uncertainties drive the performance of individual systems and the integrated architecture. Any negative issues that may be experienced result in diminishing reliability and increasing operational disruption.

"Level of obsolescence" defines the uncertainty in not being able to find replacement parts. As obsolescence increases, with the arising need to source alternative parts, the reliability diminishes due to the new parts that are introduced to the system.

"Rate of capability upgrade" involves technological advancements that are made along the equipment life cycle to enhance equipment capability. It creates the uncertainty of how the system will respond to changes. Furthermore, "Capability upgrade" can be made with the ambition of reducing uncertainty in "reliability".

"Quality of components and manufacturing" is associated to the reliability of parts that have been developed either internally or externally, which involves uncertainty in the quality. There is a correlation between the quality and reliability.

"Sufficiency of spare parts", when considered at the integrated system level, influences the operation of other integrated parts which affect the reliability.

"Rate of rework" largely originates from errors in maintenance, which causes rework in the service provision. As a source of uncertainty it has an influence over reliability.

"Failure rate of software" and "Failure rate for hardware" have a direct influence over the reliability of equipment. The uncertainty is associated to the when, where and how significant the failure is.

"Maintainer performance" considers service delivery from a resource dimension. The uncertainty originates from human centred drivers such as skill and motivation, which influence how the reliability evolves.

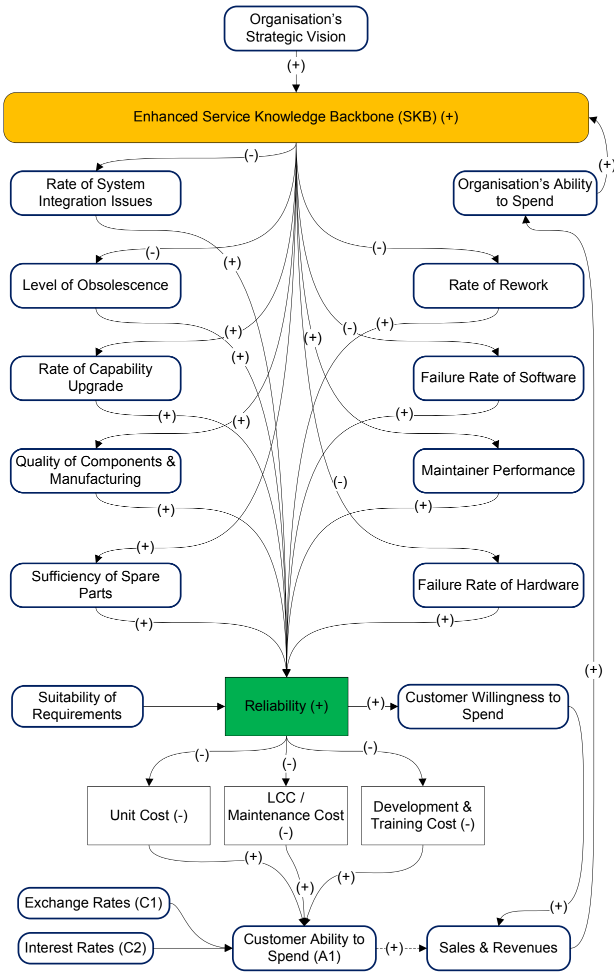


**Figure 4: DKU Causal Loop Model – SKB, Reliability and Uncertainties**

"Reliability" forms a central focus of the Service Knowledge Backbone. Any shift in "reliability" directly influences "Unit cost", "Maintenance cost", "Development and training cost". Such changes fundamentally affect "Customer ability to spend" and "Sales/revenues". The cost of purchase of new equipment and services will vary driven by the proposed reliability level. The spend will be in purchase of new equipment and services rather than on the maintenance costs that have now been reduced – i.e. it encourages a long term increase in OEM revenue not short term.

The digital framework will be developed in MS Excel® and aims to be used as a decision support tool. The main advantages of using MS Excel® are associated to its: (1) wide use and availability, and (2) flexibility to make changes. The step-wise input process will involve two sets of input requirements to facilitate qualitative and quantitative analysis. Firstly, the user will be offered to choose from a pre-defined set of attributes, uncertainties and service knowledge types based on their relevance to the project/research at hand. This will assist the qualitative analysis, mainly based on a tick box type approach. Secondly, the quantitative analysis aims to illustrate the degree of dependency between uncertainty and attributes as well as between knowledge and uncertainty. Various approaches such as the analytic hierarchy process, which facilitates pair-wise comparisons, will be implemented to reflect the significance of each element. As an output the tool will show the link between uncertainties and knowledge. The tool will offer further analysis to reflect the benefit in reducing/increasing uncertainty by making a change in the knowledge level.

The limitations of the DKU framework may include a fewer industrial testing, which needs to be applied widely in the industry. The framework could also be compared and tested on platforms other than MS Excel®.

## 6. CONCLUSIONS AND FUTURE WORK

This paper presents DKU framework that supports decision making in understanding the link between the level of knowledge and uncertainty in life cycle design within aerospace sector. Additionally, the related preliminary CLMs are proposed in order to visualise the application. The paper focuses on addressing two major challenges:

- How can the influence of knowledge on uncertainty be captured and demonstrated?
- How can the implications of changing the level of knowledge or uncertainty be illustrated?

Based on initial feedback, through industrial interaction (including semi-structured interviews), there are a number of implications of the proposed framework for decision-making. The framework supports efficient and effective product design through visualisation of the service impact of design decisions at an earlier stage in the life cycle where greater design freedom exists. The framework also supports demonstrating the link between achievements of the design attributes and the associated knowledge and uncertainty. This enables us to build an understanding of how uncertainties can influence achievement of attributes and how knowledge could be used to reduce the influence. To summarise the following key industrial benefits are envisioned by implementing the DKU framework:

- Reduced life cycle cost;
- Enhanced, cost effective product & service design;
- Better targeting of knowledge requirements; and
- Improved understanding of the implications of uncertainty on life cycle design.

The following future work is recommended:

- Building and further enhancing relationships between knowledge and uncertainty;
- Building and further enhancing a dynamic relationship between knowledge based uncertainty and the design implications;
- A mechanism to illustrate the value of changing the level of knowledge in relation to the degree of uncertainty and the implications of this on the life cycle design. Also to have a cost-benefit analysis of enhanced knowledge;
- Need for frameworks to assess the knowledge level for design attributes;
- Mathematical optimisation of attribute set (over time) given the influence of uncertainty;
- Assessment of the value of knowledge;
- Comparison of existing vs. required capability and seeking benefits (if any) in changing the knowledge value;
- Further exploring the role and methods for through-life engineering service knowledge feedback to product design and manufacture in life cycle engineering.

Despite all these benefits, there are few limitations of the DKU framework in its limited testing in different industrial sectors. It's also limited to MS Excel® based software platform, which may be explored in future to apply on other platforms as required by other industries.

## 8. ACKNOWLEDGMENTS

Rolls-Royce plc, EPSRC and Technology Strategy Board are acknowledged for providing funds to Service Knowledge Backbone Project (Knowledge Transfer Partnership Program No. 7767). KT-Box Project partners are also acknowledged for providing funds. Authors are also grateful for kind support from the Cranfield IMRC for funding this research and the industrial partners for their support.

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