

UNCERTAINTY IN THROUGH LIFE COSTING WITHIN THE CONCEPT OF PRODUCT SERVICE SYSTEMS: A GAME THEORETIC APPROACH

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ABSTRACT

By 2028 Rolls-Royce predict a civil after sales market opportunity of USD 550 billion and for military engines of USD 300 billion. Naturally, with this anticipated business Product Service Systems (PSS) have experienced a growth in interest by both industry and research. To achieve effective and profitable PSS, the Through Life Costs (TLC) of products/systems needs to be considered comprehensively. However, uncertainty in the estimation of future factors such as operation costs, level of maintenance and so on make this extremely challenging to estimate and model. The research introduced in this paper proposes that Game Theory might be of value for modeling the uncertainty in costs arising from conflict situations in the life cycle. Therewith, the decision making process can be modeled and so be made visible with its various implications. To introduce this proposed approach a review of the literature in PSS, TLC and uncertainty is summarized and then applied to this proposal. The results of preliminary and further work will be described.

Keywords: Product Service Systems, Through Life Cost, Life Cycle Cost, uncertainty, decision making, Game Theory

1 INTRODUCTION

Sustainable production and consumption has become a high priority internationally [1]. As part of this a transformation of market structures and competitive situations has been noticed [2]. This is prominent in countries with high wages and labor costs. To address this change, the exploitation of servitization has been proposed as a possible way to stay competitive and earn the required unique feature that separates its products from technically similar rival products [1]. The service component of most countries of the Organization of Economic Co-operation and Development (OECD) has expanded rapidly since the late 1990's and is still valid [3]. This shift to a "service economy", where the service component accounts for between 50% and 75% of jobs and added value [4], is not only related to traditional services such as financial and legal sector, but also to new product-service systems.

A Product-Service System (PSS) is a special case of servitization and has various definitions [5, 6]. It can be defined as a marketable, integrated combination of products and services [7, 8]. Therefore, a PSS can be thought of as a market proposition that extends the traditional functionality of a product by incorporating additional services. The product-service ratio can vary, either in terms of function fulfillment or economic value, to deliver customer value [9].

According to the product-service ratio, the following types of PSS can be distinguished [4, 8]:

- Product-oriented PSS: The ownership rights of the material are transferred to the customer, in other words, the customer becomes the new owner of the product. A service arrangement is provided to ensure the utility of the product over a given period of time. Examples for this type of PSS are warranties and maintenance contracts.
- Use-oriented PSS: The ownership rights of the product stay on the site of the producer, the customer purchases use of the product over a given period of time or units of service. Examples include leasing and sharing schemes.
- Result-oriented PSS: The ownership rights stay on the site of the producer, the customer

purchases the result or the outcome of a product. An example is described as the delivery of clean clothes rather than the sale of a washing machine.

In particular, use-oriented and result-oriented PSSs encourage the producer of the product to improve the functional optimization of the product itself and its performance because they stay accountable for it. The responsibility for a product's whole life cycle or its ownership is transferred from the customer to the producer. Therefore, PSS do not only consider the design and construction of a product, but the whole life cycle starting from its conception and finishing at its disposal/refurbishment. Section 2, introduces the research challenges for Through Life Costing and in particular describes how these are currently modeled. Section 3, then describes uncertainty and how this can be applied within TLC modeling. Finally, the usage of game theory within this context is discussed and its possibilities analyzed.

2 THROUGH LIFE COSTING

Using Through Life Costing (TLC) as a method for optimizing the design of physical assets has had a long history in the theoretical research in manufacturing and construction. Much work has been done on developing the concept and its effects [10, 11]. Different terms have been used, including "Terotechnology", "Whole Life Costing", "Life Cycle Costing", "Costs in Use", "Total Costs of Ownership", "Ultimate Life Costs", and "Total Costs" with variations in the meanings of these terms [11]. This article adopts the definition provided by the British Standard Institute (BSI) [12]. In summary the term TLC is similar to the term Life Cycle Cost (LCC) used in the standards [13, 14]. The standards made a distinction between the systems of TLC and Whole Life Cost (WLC), as illustrated in Figure 1. TLC is defined as the cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements. This can include e.g. production cost and operations cost. WLC includes all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements. Therefore WLC not only includes TLC, but also project-external costs, such as taxes or finance costs.

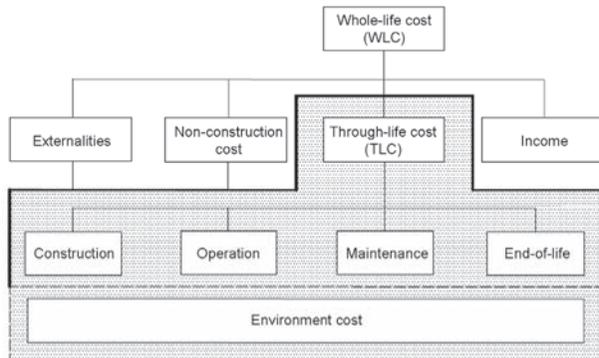


Figure 1: WLC and TLC elements [15]

Estimating the costs of a new product is an important factor for the success or failure of a project [16]. Many researchers have pointed out the significance of cost estimation, especially during the early design stages of a product, where 60-80% of the total product cost are determined [e.g. 16, 17]. In complex engineering systems, such as defense procurement and aerospace, the life cycle cost can be many times the initial purchase costs [18, 19]. Therefore, the costs of a new project development need to be identified and understood before it actually begins.

2.1 Aims and use of TLC

The aims of TLC can be multifaceted, according to the depth of implementation of the concept in the user's day-to-day business. The obvious ambition is the optimization of the life cycle costs of the asset

ownership. The costs of purchasing the asset as well as the future costs of operating (including maintenance) and disposal/reuse of the item are being revealed and can be taken into consideration, to form the basis of future decisions concerning design, scheduling, and planning. Another aim can be the control of the operation and maintenance costs of an asset in the decision making process [19-21]. To do so, the process of TLC includes the identification and the quantification of the significant costs and pooling them in a database.

As stated before, the aims of the TLC implemented in a company's business, depend on how it is used. Two levels of usage can be distinguished: TLC as a "Management Tool" or as a "Management System" [11]. TLC represented as a "Management Tool" constitutes the lower level of use and aids the decision making process. It helps to make an effective choice between a number of competing alternatives. This can be at any stage of the project, but most potential lies in the early design stages. Then, most of the options are open for consideration and significant capital expenditure is yet to be committed.

The implementation of TLC as a "Management System" extends to the continuous operation during the asset management. On this account, TLC can be applied in all stages, except concept and definition. The actual costs incurred in operating an asset are identified and can be used as an early indicator for problems that might occur. Also, the actual costs can be measured and compared to the planned ones, which enhances the accuracy of future estimation processes. Furthermore, it helps the higher management to have an up-to-date impression of the performance of the existing technology and the possibilities for enhancing it.

Although there are a lot of advantages connected to the implementation and usage of TLC, it also demands significant effort and costs in collecting the necessary data and information. So it is important to know, if the results of TLC are crucial for the considered problem or are just "nice to know". The application of TLC to products with short life cycles due to quick technical innovation, such as mobile phones, does not seem to make sense. Assets, where the use of TLC is especially important, can be:

- assets with short life expectancy and a high operation cost-acquisition cost ratio,
- assets with long life expectancy (both low and high operation cost-acquisition cost ratio) [10].

The boundaries between these categories are not clearly defined, but to understand the classification better, examples are illustrated in Table 1.

Table 1: Assets where the application of TLC can be important

		life expectancy	
		short lived	long lived
operation cost acquisition cost	low	mobile phones	building
	high	electro-mechanical (with high consumption)	plant energy aircraft, waterworks pump

- assets, where TLC is not useful
- assets, where TLC is important

2.2 TLC modeling

TLC modeling techniques can be based on the comparison to previous projects or products or they can include a detailed analysis of a product design including its components, features, manufacturing processes. Despite the cost estimation technique used, a set of procedures are followed to make the costs and cash flows comparable to one another. To make this possible, the time value of money needs to be considered, meaning that a certain amount of money today is worth more than the same amount at a point in the future [11]. The basic logic is expressed in equation (1):

$$m_p = i_t \cdot m_f \tag{1}$$

with m_p being the present amount of money,

m_f being the future amount of money, and

i_t being the factor required to transform future money to present money.

One important method is the calculation of the net present value (NPV) of future cash flows of a project (or of the costs of a product to the company) using the following equation [22]:

$$NPV = \sum_{n=0}^T c_n (1+x)^{-n} \quad (2)$$

with c_n being the nominal cash flow in the n th year,
 n being the specific year in the life cycle of the product,
 x being the discount rate,
 T being the length of time period under consideration, in years.

Future amounts of money, be it costs or returns, are discounted to a today's value, using a discount rate. This rate can include not only the time preference of money, but also inflation, taxation, and future economic development [11].

TLC and cost estimation are disciplines that attempt to forecast the future, sometimes even a long way ahead in time, according to the project or product of concern. They consequently have to deal with uncertainty introduced by factors such as life cycle events, discount rates, operation, and maintenance that have an impact on the performance of a project. Uncertainty is endemic to the processes of TLC [11]. Thus, the treatment of uncertainty in an adequate way is essential for the success of the project.

3. UNCERTAINTY

Many opinions exist on what uncertainty is and how it can be defined [22-26]. The most general view of uncertainty was given with the definition that uncertainties are things "*that are not known, or known imprecisely*" [23]. A more detailed definition can be made by saying that uncertainty occurs in a situation when a decision maker "*does not dispose about information, which is appropriate or necessary to describe, prescribe or predict a system, its behavior or other characteristics*" [24].

3.1 Reasons for uncertainty

Due to the definition of uncertainty, a main cause of it is the lack of knowledge [25-27]. As many sources use the terms information and knowledge simultaneously, various authors have pointed out the difference between them [25, 26]. Information is an important input especially at the early phases of product design. An information element describes a fact, with the fact being an occurrence of a measure or inference of a certain quantity or quality. Thereby, the fact can be objective or subjective and can be communicated through different channels, such as speech, body language, reports, and drawings. However, knowledge is generated by processes, taking place within an individual's mind through the understanding, assimilation and application of information.

A lack of knowledge is created, when the information needed is not provided for any reason. Further classification can be undertaken in terms of quantitative and qualitative lack of knowledge. An example describing quantitative lack of knowledge would be that the decision maker does not have any information about which of the possible states of nature will occur. A qualitative lack of knowledge occurs when the needed information is available but does not describe the situation deterministically. Reasons for these states can be uncertainty in the data collected, i.e. due to impossibility of measuring physical data precisely [27, 28].

Another cause for uncertainty is the lack of definition, also named as imprecision [29]. This concerns things about the system that have not been decided or specified yet, e.g. the design of a new product. Other criteria can also cause uncertainty such as the abundance of information due to the limited ability of human being to perceive and process simultaneously large amounts of data [30], as well as ambiguity due to the fact that certain linguistic expressions have entirely different meanings [31]. Uncertainty can also occur when there is conflicting evidence, which describes the fact that different bits of information can point to conflicting behavior of a system, and belief, which examines the situation when all the information available is subjective. Figure 4 illustrates this classification.

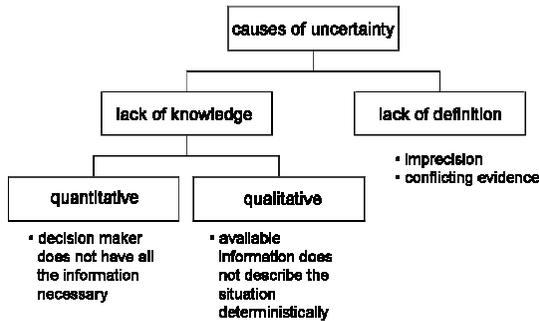


Figure 2: Classification of the causes of uncertainty

3.2 Methods to model uncertainty

As a result of the diversity of the causes of uncertainty the models of treating it are various as well. Only the major approaches, namely probability theory, Monte Carlo, fuzzy set theory, and interval analysis, will be discussed here. Probability theory is used when there is variability in a certain characteristic of a system or product, called stochastic uncertainty [32]. It was perhaps acknowledged first by the saying “*the strength of a chain is the strength of its weakest link*” [33]. Probability theory is an established approach for use in safety and performance analysis in all branches of engineering to ascertain the probability of failure (POF) and risk. In particular, it has been used to describe the strength of building material, such as timber and concrete. Therefore, a statistically large number of sample sizes of the considered characteristic are tested and evaluated. The result is fitted with a probability density function (PDF) that shows the probabilistic quantity of X over the domain of possible values. The most commonly used PDF is in the form of a Gaussian distribution [34, 35]. A simulation approach based on probability theory is the Monte Carlo Method [36-38]. The Monte Carlo Method uses the law of large numbers to pseudo-randomly sample the problem of interest many times and the results fitted with a PDF, which can then be used for further inspection of the problem. This method is used in many areas, e.g. of business operation [36], costing [37], and engineering [38]. One main area is to price options in the financial sector, especially path-dependent options. An alternative approach is the fuzzy set theory [35, 39, 40]. The theory of fuzzy sets was first introduced in 1965 by Zadeh and is suitable to describe linguistic, incomplete information in a non-probabilistic manner. A fuzzy set is defined as a class of objects with a continuum of grades of membership, meaning that it is characterized by a degree of membership, embodied by a membership function. Fuzzy set theory is used to represent and manipulate the imprecision aspect of uncertainty in design [29]. Another approach is the interval analysis which is applied if the uncertainty cannot be expressed by using a PDF because precise probability information is not available. In that case the variable x is described with the help of an interval [41].

4. DECISION MAKING UNDER UNCERTAINTY

TLC deals with the future of the considered product or project and the future is not known. In an uncertain world good decisions can lead to bad consequences and vice versa [42]. Therefore, the treatment of uncertainty in information and data is crucial for a successful application and usage of TLC. Uncertainty in investment decision-making can be defined as decision-making where different values of criteria for each investment alternative are predicted under the fact that it is not known which alternative will be realized in practice [43].

The existence of uncertainty in the area of TLC is widely acknowledged in literature [42, 43]. However, there are only few techniques that help managing the problem. In general, the techniques mentioned in section 3.2 to deal with uncertainty are applicable. These are for example Monte Carlo Method and Fuzzy set theory. One well established method, developed to deal with uncertainty in

TLC, is the sensitivity analysis [43]. It helps to ascertain the influence of certain variables on the project's outcome.

4.1 Game Theory

From the review and initial industrial interactions, it is proposed that a method for supporting decision making under uncertainty associated with TLC will be valuable. Game Theory has been applied to illustrate different decision making processes [44]. It provides a theoretical underpinning for most areas where economics are involved. A Game is a model of a situation where two actors compete with each other [45]. Game Theory describes any interaction between two (or more) players (also called agents) that is governed by a set of rules and a set of outcomes. The rules specify the possible moves each player can undertake, the set of outcomes explain the result of each possible combination of moves. It was first published in 1944 by von Neumann and Morgenstern and has spread its possible application to almost every situation of social interaction since then [46, 47].

The basic theory builds on the following assumptions:

- Individual action is instrumentally rational: This is the basic and most important assumption of the theory. Every individual who is instrumentally rational has preferences over various things. And this individual will select these actions that will best satisfy those preferences. In case of a preference of choice A over B and B over C, the person also prefers choice A over C.
- Common knowledge of rationality: The opponent is instrumentally rational likewise and therefore his/her actions can be predicted. In other word, the opponent's actions can be modeled.
- Common priors: The agents share the same view of what they are and draw the same inferences on how a game is to be played. They carry out the same thought processes, have a consistent alignment of beliefs and use the same information. Therefore, an instrumentally rational player will not be surprised by any of his opponents' actions or moves.
- Action within the rules of the games: This assumption includes two parts: first, every individual knows the rules of the game; second, every person's motive to act is strictly independent of the rules.

There has been contradicting opinions on the usefulness of Game Theory in forecasting. It has been argued that Game Theory provides better results than current methods when used in forecasting, especially in conflict situations [48-50]. Fundamental research was undertaken by Armstrong [51]. His findings were that the usage of role playing to forecast the outcomes of conflicts provides more accurate results than those made by experienced game theorists. Goodwin [49] named two main problems of using Game Theory in forecasting, based in the assumptions stated above: the incompleteness of information available and the agents not behaving instrumentally rational.

These assumptions have undergone iterative changes in order to be applicable to different situations and rules [52]. Especially the picture of an individual as a rational decision maker has been replaced by the theory of bounded rationality [e.g. 42, 52, 53]. Therefore, the bounds on the players' rationality have been described as various. First, limits are put on the decision making process by the limited complexity of states ascertainable by an individual [53]. The players are only able to base their decisions on strategies and outcomes understandable and traceable for them. Second, the decision makers learn, i.e. they change their underlying attitude of the world according to stimuli [42]. Hence, the same decision making problem at different points of time can lead to different outcomes.

Game Theory can be divided into cooperative and non-cooperative games, according to the agents being able to communicate with each other or not [54]. In cooperative games, the agents can form coalitions in order to influence the outcome. Non-cooperative games focus on the individual agent whose main interest it is to maximize his/her outcome [54]. Connected to these types of games is the concept of the outcome: either Nash equilibrium or Pareto efficient solution [45]. The Nash equilibrium occurs when both (or more) agents act in order to maximize their own outcome, no matter which action the other player chooses. A Pareto efficient solution can be characterized as an overall optimal outcome, i.e. where every individual agent chooses the action that optimizes the whole group/company [45].

It has been discussed to use Game Theory in early design stages in order to model the impact of different design solutions on the final product [54]. The so called leader/follower model has been applied in engineering design to model the influence of one discipline to another in a strictly unidirectional decision making chain [55]. This model contains two players of the same team/company

and does therefore fall into the category of (non-)cooperative games based on Pareto efficiency. Unfortunately the existence of uncertainty was ignored in that application.

4.2 Game Theory under uncertainty

A bidding situation under uncertainty falls under the category of non-cooperative games based on the concept of Nash equilibrium. Game Theory in uncertain situations can be divided into games against an intelligent opponent and games against Nature [43, 56]. Games against an intelligent opponent have been touched on above, stating the assumption that the opponent behaves in a (bounded) rational manner. Games against Nature are harder to model, as the opponent is Nature and therefore the moves or actions cannot always be predicted. In other words, the opponent's behavior is uncertain. It can be presumed, that no reliable information about possible moves is available and so the choice is free.

The usage of Game Theory to support decision making in TLC and cost analysis has not yet been explored in research. It is hypothesized that Game Theory can be used to improve decision making involving TLC, where the costs and events are driven by a number of players. It may offer some values in terms of understanding TLC where the situation is not only influenced by the producer, but also the competitors and consumers. However, the area of an opponent whose behavior is uncertain has not yet been analyzed comprehensively. Therefore, no case studies or research results are available on how to overcome or model the behavior in this environment. It is suggested to apply Game Theory as a Management Tool as discussed in section 2.1 in order to support the process of TLC.

However, first steps have been undertaken into the direction of modeling decisions under uncertainty by defining relevant environmental input variables [57-59]. Therefore, a decision making problem under uncertainty can be described by the set of states of Nature S_i , the set of possible acts for the decision maker A_j and a set of consequences C_{ij} (also called payoff). If the decision maker chooses action A_j and the state of nature is S_i , the consequence C_{ij} will occur, as shown in Figure 3. The consequences include everything the decision maker cares about, i.e. he/she has preferences over the outcomes and nothing but the outcomes. The acts and states themselves have no positive or negative value themselves [60].

$$\begin{matrix}
 & A_1 & \cdots & A_j & \cdots & A_n \\
 \begin{matrix} S_1 \\ \vdots \\ S_i \\ \vdots \\ S_m \end{matrix} & \begin{bmatrix} C_{11} & \cdots & C_{1j} & \cdots & C_{1n} \\ \vdots & & \vdots & & \vdots \\ C_{i1} & \cdots & C_{ij} & \cdots & C_{in} \\ \vdots & & \vdots & & \vdots \\ C_{m1} & \cdots & C_{mj} & \cdots & C_{mn} \end{bmatrix}
 \end{matrix}$$

Figure 3: Decision matrix

Uncertainty is caused by the fact, that the future state of Nature S_i is not known, described as quantitative lack of knowledge in section 3.1. At some point in the future one and only one of the possible states of Nature will occur [60]. However, it may be possible that not all potential states of Nature can be described comprehensively. In some cases, the decision maker may not have any knowledge about the potential state of Nature other than it lays within the set S. This situation has been discussed as decision making under ignorance [59]. Another reason possibly resulting from the above is that the consequences of the decision maker's actions may not be known at all or only incompletely [42]. The objective of research is to define how rational a decision maker can act, facing those uncertainties in a cost estimating process.

It has been discussed that, no matter how the information is presented, the decision maker's reception of it is subjective [61]. This is caused by the conception and interpretation of the information which can differ from person to person due to different mental ability to deal with the abundance of information [30]. Another aspect of subjectivity is the degree of belief that may be different between

different persons. The degree of belief is the subjective probability an individual may associate with a certain state of Nature in the future [62]. Evidently, certain vagueness will inhere in a shared language when communicating uncertainty between different people. Much work has been done in order to formalize the uncertainty inherent to the subjectivity of the actions of a person [63, 64].

Different decision makers can also differ in their attitude against Nature. Therefore, the chosen action can also depend on the decision maker being pessimistic, optimistic or neutral [59]. A pessimistic person will see its opponent as malevolent, meaning that the opponent will try to minimize the player's payoff C_j . The decision maker will therefore choose the action with the maximum of all minimum payoffs for every possible state of Nature [59]. This strategy can be devolved to the optimistic decision maker, namely that the chosen action will then be the one which maximizes all possible maximum payoffs. The valuation function $U(i)$ of the decision maker can then be put as

$$U(i) = \text{Max}[\text{Min}(C_{i1}, \dots, C_{ij}, \dots, C_{in})] \quad (3)$$

for the pessimistic approach, and

$$U(i) = \text{Max}[\text{Max}(C_{i1}, \dots, C_{ij}, \dots, C_{in})] \quad (4)$$

for the optimistic approach [59]. In general, a decision maker's attitude can be expected to be somewhere in between these two extreme values [65], namely

$$U(i) = \alpha \cdot \text{Max}[C_{ij}] + (1 - \alpha) \cdot \text{Min}[C_{ij}] \quad (5)$$

with α being the degree of optimism, $0 \leq \alpha \leq 1$.

The closer α is to 1, the more optimistic is the decision maker. This formula has been discussed as the Hurwicz criterion in literature [59].

Thus, each decision maker can be described by his/her strategy, based on the attitude and expectations. A strategy is therefore defined as being deterministic, meaning that it always leads to the same "optimal" action giving the same decision matrix [64].

In this context, the existence of a so called robust action has been discussed [65]. This is defined as an action that gives "good enough" or satisfying payoffs against any state of Nature S_i occurring. In most decision making scenarios an absolute robust action does not exist due to the fact that it might not be possible to describe all states of Nature comprehensively or the decision matrix does not include a robust action. Thus, the existence of an approximately robust action has been discussed. This results in a satisfying payoff in almost every state of Nature.

The uncertainties related to the person of the decision maker can be summarized as inconsistency of preferences, vagueness in the interpretation of aspects of the model or their scope, unawareness of possible states of Nature and failure of logical omniscience [42].

5. CONCLUSION AND SUMMARY

Within the development of servitization, especially for the development of PSS, the consideration of TLC is important to ensure sustainability. Therefore, it needs to be undertaken profoundly. Simple methods are necessary to alleviate the application of TLC in industrial surroundings. The consideration of uncertainty in TLC is inevitable to support robust decision making. However, the possibility of the application of different models and methods has not yet been analyzed comprehensively. This area of research especially lacks easy to apply and to understand models to treat uncertainty particularly in the early phases of a product's life cycle.

Game Theory seems to be a promising area to model uncertainty in decision making processes in the field of TLC. In some of these situations uncertainty may be understood better and therefore treated more accurately with the usage of Game Theory. However, further investigation especially on where it applies needs to be undertaken. It was shown that the perception of uncertainty depends not only on its presentation but also on the decision maker's expertise, attitude, knowledge and understanding. It is therefore essential, to present the game in a simple and user friendly way [63]. Thus, it is important to understand what type of information needs to be fed into the decision making process and how much detail is needed in order to make a qualified decision. In the early design phases, only limited

information is available. The conclusions and forecasts based on that information still need to fit for purpose and be valid for different variances of the product [66].

To support that, a first experiment is being undertaken in order to find out, how information needs to be displayed and how detailed it needs to be. Therefore, costing experts of different stages of experience will be given different demonstrations of a forecasting problem and will be asked for their opinion and decision on it. The graphical demonstration of a forecasting problem has been proved to be the best way to make a decision maker understand a problem and give an accurate estimate [e.g. 67]. This will give an understanding of how uncertainty is/ needs to be communicated. The outcome of that experiment will give the following results:

- the best way to display a forecasting problem,
- how much information on the background of the problem situation needs to be given,
- how detailed the information needs to be explained.

A second experiment will introduce the idea of Game Theory to the forecasting scenario. Therefore the scenario of bidding against an (unknown) opponent will be described. This experiment will show how the existence of a rival situation influences the forecasting and decision making process.

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