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REFERENCE SCHEME FOR DERIVING ASPECTS AND CRITERIA FOR FORECASTING FUNCTIONAL PERFORMANCE AND COST IMPLICATIONS OF CYBER-PHYSICAL PRODUCTS

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ABSTRACT

Forecasting techniques are used in many application fields. In product and system engineering, they can provide means to predict various aspects such as costs, economic advantages of investing in the product or system, running expenses, and the environmental consequences. Forecasting techniques can support affordability, quality and acceptability related decision making processes during design. The work presented in this paper focused specifically on cyber-physical products (CPPs). One of the major challenges that the users or developers of new CPPs are more likely to face is how to justify early on if it is worthwhile to invest in CPPs rather than in traditional products. The work presented in this paper is part of a larger research that attempts to address this challenge. Specifically, we explored how the benefits and shortcomings of investing in new CPPs could be predicted accurately early on in the product development process. We have reviewed and analysed the existing literature and practices with a view to identify the approaches that could possibly be used in assessing and forecasting functional performance and cost implications of CPPs. Based on a proprietary feature-based definition of Cyber-Physical Systems, we have identified the global categories of CPPs features, and subsequently proposed a reference scheme for deriving aspects and criteria for assessing functional performance and cost implications of new CPPs. We use a practical example to illustrate the applicability of the proposed reference scheme.

KEYWORDS

Cyber-physical systems, feasibility analysis, forecasting, economic advantage, engineering design

1. INTRODUCTION

Forecasting can be described as the process that involves (i) using information or data and formal models, or (ii) relying on e.g., hunches and past experiences - to make statements about the likely courses of future events [7]. Some literature argues that for certain specific forecast settings; there must be an optimal model or forecasts that only need tuning by experts [6]. Forecasting techniques are used in many fields of applications; most commonly in financial markets [1], management [22], and meteorology [18]. In product engineering, various approaches are presently applied to predict and assess the implications of investing in products, including for instance: in predicting and controlling cost [16, 20], and in estimating the effort that needs to be invested in product development [23]. The existing approaches are typically applicable to functionally and structurally linear products (i.e., product with relatively few interacting autonomous physical, cyber and/or software components) and are mostly used in latter stages of the product development processes (e.g., when the details of the product and of its components have already been finalized and are fully known).

In recent years, a new class of consumer products, variously known as Cyber-Physical Systems (CPSs), Cyber-Physical Products (CPPs), or Cyber-Physical Consumer Durables (CPCDs) has emerged – see e.g., [24, 25]. Unlike the traditional products or consumer durables, cyber-physical products or systems are integrations of computation and physical processes [26, 27]. Computing, communication, and control technologies are tightly connected, and the embedded processors and networks monitor and control physical processes (usually via feedback loops). The physical processes affect computations and vice versa [13, 14]. The differences between the traditional products and CPPs also arise from the nature of the processes involved in their realization, how they are assembled, and how they are applied (i.e., the way they provide service, the way they are operated or operate, the way they are maintained, the way they adapt themselves to situations, and so forth). One of the unique characteristics of CPPs is that many events in them happen at once. In other words, physical processes are compositions of multiple parallel processes occurring simultaneously while software processes in them are deeply rooted in sequential processes - see e.g. [4]. In addition, they deeply penetrate into the natural and created environments, and into the social and cognitive domains of people and communities. Designing and development of such systems typically requires in depth understanding of the dynamics of computers, software, networks, and physical processes [15].

One of the major challenges faced by the developers and users of CPPs is the ambiguity associated with the probable functional performance and the cost implications of CPPs. It is extremely challenging to predict how a CPP will perform and to justify the benefits of investment early on, especially in the so-called fuzzy front-end of the development process. In particular, it is often difficult to predict cost implications and performance of a novel and highly innovative CPP. Likewise, it is difficult to predict what impact a CPP would have on both natural and engineered environments. For instances, there might be an obvious need for new functional features, but the developers often face the dilemma in deciding on whether or not to incorporate the new features into the product or system because of uncertainty associated with the impacts or cost implications. Furthermore, some of the key technical requirements (which are in the first place supposed to be the basis for incorporating new functionalities into the product) sometimes come too late due to the evolving nature of the requirements [5]. We argue in this paper that the existing approaches and the practices adopted by organizations to predict and assess the implications of investing in traditional products cannot be applied straightaway to CPPs. Consequently, there is an apparent need to come up with a comprehensive and multi-aspects forecasting and prediction strategy, which is appropriate and capable of addressing the challenges discussed above. In short, the main research question we dealt with in this paper can be summarized as follows: What sorts of assessment and forecasting criteria and strategies could be used in the early stages of the product development process to explore feasibility, cost implications, and the economic advantages of incorporating new physical, software or cyber features in a CPP?

The specific goal of this paper is to introduce a reference scheme that we hypothesized to be a fundamental epistemological and methodological framework for developing a computer-based enabler for deriving comprehensive assessment and forecasting aspects and criteria. The paper is structured as follows. The following section elaborates the research problem and approach. Section 3 reviews the practices presently used in assessments and forecasting. Section 4 discusses the issues that should be considered and the challenges faced in forecasting. Section 5 presents the proposed reference scheme for deriving aspects and criteria for assessing and forecasting the implications of making a product cyber-physical. Section 6 highlights the implementation issues. Section 7 illustrates how the reference scheme proposed for deriving aspects and criteria for assessing and forecasting the implications can be put to use. Section 8 discusses the research results and future research, and Section 9 briefly summarizes the paper and presents the main conclusions.

2. ELABORATION OF THE RESEARCH PROBLEM, FOCUS AND APPROACH

The real challenges in assessing and forecasting functional performance and viability of CPPs (including e.g., the analysis of feasibility, incurred costs and economic advantages) arise from: (i) the inherent complexities of these products, (ii) the complexity of the processes by which they are developed and produced; (iii) the embedding and integration of computational and networking capabilities; (iv) the diversity of the software, cyber and physical components that constitute these products, and the (v) distributed nature and the challenges inherently associated with distributed operations of these products. As for operation and service providing, achieving the anticipated level of quality, reliability and security of computational, networking and physical elements in operations while hitting target operation costs or meeting environmental or terminal device constraints are of paramount importance. The features of CPPs, the ways these features are realized, and the way CPPs operate drive the need for an effective strategy of assessing and forecasting functional performance, structural feasibility and cost implications of CPPs. As a first step in addressing the above-mentioned challenges, we conducted a preliminary literature review and analytical investigations with a goal to explore the techniques presently used in assessing and forecasting functional performances and cost implications of products. At the same time, our intention was also to know the potentials and specificities of these techniques as well as the inherent characteristics of CPPs (including their development and use processes). We have identified some elements of the existing forecasting techniques and prediction drivers which could be considered and incorporated into a framework for assessing and forecasting functional performance and cost implications of CPPs.

This paper presents the results of the research we have conducted so far. Through analysis of the existing literature and practices, we established that a comprehensive reference scheme is needed to support (i) specification of the important considerations and aspects of assessment, and (ii) deriving the criteria for assessing and forecasting functional performance and cost implications of CPPs. Specifically, in this part of the research, we reviewed related literature and practices with a view to answer the following questions: What is forecasted or assessed in design intervals and how this is accomplished? What techniques are used in forecasting and in assessing the implications of investing in products? Which features and characteristics differentiate traditional products from CPPs? Which features of the traditional products are comparable to CPPs? What drives forecasting processes? Which parameters, attributes and metrics are used in forecasting?

We then defined typical types of CPP features and subsequently proposed a scheme for deriving aspects and criteria for assessing and forecasting the likely consequences of investing in CPPs - in early life-cycle stages (i.e. during the feasibility analysis phase - when even the requirements and details of the CPP in question or its components are not yet fully known). The intention is to have in place an effective assessment and prediction strategy that relies only on: (i) the limited understanding of the requirements for a CPP, (ii) the preliminary underlying concepts of a CPP, (iii) the initial ideas on how the CPP would be produced, and (iv) on the preliminary understanding of how the CPP would be used or operated. The hypothesis is that '*based on a properly compiled body of knowledge, acceptable assessment and prediction of functional behaviour and performance of a CPP as well as of its cost implications can be made in the early stages of the development process*'. We use an application example to illustrate the applicability of the reference scheme we proposed for deriving assessment and forecasting aspects and criteria.

3. ANALYSIS OF THE PRACTICES CURRENTLY USED IN ASSESSMENT AND FORECASTING

In this Section, we explore and analyse the state of the art of the existing forecasting practices, with a view to understand the potentials of the techniques used and their relevance in the context of this work. The goal was also to identify desirable characteristic features and requirements for an effective methodology for forecasting functional performance and cost implications. Several predictions and assessments are performed in the design interval. These include predictions and assessments of cost, likelihood of failure, failure mode, economic advantage, sales, likely courses of future events (e.g., performance), and the relevance of the final product (Figure 1). For the developers of CPPs, cost implications of the choices made in early design phases is one of the most important assessments and aspects of prediction. This is due to the existence of direct association of cost with the affordability and acceptability of the product. Various approaches are used to predict and analyse cost of the traditional physical (hardware) and software consumer products. And different kinds of expenses can be predicted, including e.g., product development cost, manufacturing costs, marginal product costs and life cycle costs.

Features based costing is one of the approaches used to estimate costs. Advances in CAD/CAM/CAE and 3D modelling research led to development of feature-based costing concept – see e.g., [2] in which features are used as the basis for costing in the design phase. This concept is based on a simple perception that products have a number of features (such as flat faces, holes, folds and edges) and that each product feature has cost implications. Other methods used to estimate cost include: (i) *parametric cost modelling* – in which cost is expressed as a mathematical equation, i.e., a dependent variable to one or more variables. The equations used are derived from the analysis of historical data - see e.g., [19], (ii) *expert* *judgment* – in which experts from different domains use their experiences to predict costs. Each expert estimate cost, the estimates are then compared and discussed, and the process iterates until some consensus is reached - see e.g., [20]; and (iii) *analogy* – in which the cost of a product or a product development project is predicted by comparing the project at hand to a similar project in the same application domain. In other words, the actual cost of a previous, similar project is used as the basis for estimating the cost of the current project – see e.g., [23]. Several frameworks for predicting and estimating product costs or price have been proposed in the literature. For instance, Weustink et al. [30] proposed a framework for estimating costs and storing the cost data in a generic way which enables the user to control the product costs within the product development interval. Li et al. [16] proposed a method that can be used in production processes to control cost dynamically. Wang and Ramsay [29] present an approach that entails using a neural network to predict system marginal price. The role of neural network in their approach is to find and to determine the unknown mappings between input and output data. In general terms, the frameworks proposed for traditional products do not address the challenges typically encountered in predicting the cost implications of complex non-linear products such as cyber-physical products.

There are also several forecasting techniques that help organizations to plan for the future. These techniques include, e.g.: (a) *time-series forecasting,* in which the data gathered over time is used to identify trends, e.g., by using neural networks [1, 31]. In this case, neural networks recognise patterns in data, upon which they can then learn and eventually make a forecast of a future pattern; (b) *scenario writing,* in which different prediction scenarios can be generated based on different starting criteria and the selection of the most promising prediction is made from the numerous scenarios [9]; and (c) *Delphi technique,* which involves using questionnaires to interrogate, i.e. a group of experts – who are kept apart and unaware of each other - responds to a series of questionnaires. The results of the first questionnaire are compiled, and based on the results; a second questionnaire is presented to the experts, who are asked to re-evaluate their responses to the first questionnaire. Questioning, compilation and re-questioning continue until a narrow range of opinions is achieved [12].

Others forecasting techniques include: (d) *subjective forecasting,* in which predictions are based on subjective thoughts and feelings. In this technique, brainstorming techniques are applied to generate ideas, which are however obviously subject to biases [3]; (e) *analytic hierarchy process,* which provides a comprehensive and rational way of structuring a prediction problem, representing and quantifying the decision elements, relating those elements to the overall goals, and evaluating the possibilities. In this approach, the problem is decomposed into a hierarchy of more easily comprehensible sub-problems, each of which can be analysed independently. In addition, both the tangible and the intangible factors are considered. Typically, the forecasting process goes through the following steps: (i) identification of the factors affecting the forecasted problem; (ii) assigning priorities (i.e., numerical weights), and (iii) synthesising the priorities to obtain the overall priorities of the elements [28]; (f) *Bayesian forecasting,* in which a forecasting model is explicitly formulated based on known quantities and inferences about unknown quantities can then be drawn ([7]. In other words, based on what is known (i.e., basically using prior knowledge of structures, reasonable parameterizations, and so forth), what can be said about the future can be deduced; and (g) *model-based forecasting,* in which e.g., linear or non-linear models are developed through techniques such as regression and used to predict various aspects or future patterns [8, 17, 21].

In light of the above overview, it can be said that there are several forecasting techniques that significantly differ. Apparently these techniques have

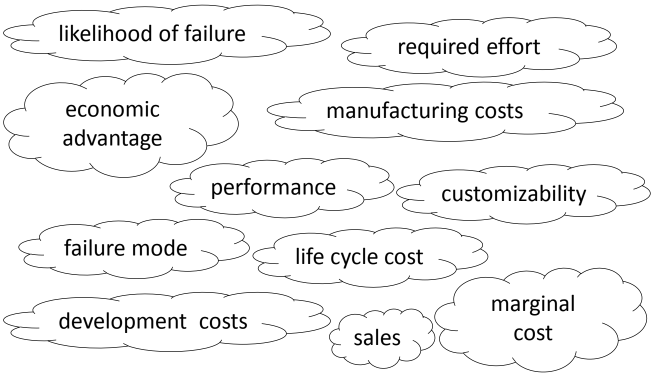

Figure 1. Examples of predictions made in the product development interval.

been developed for different purposes; and are applied under certain specific circumstances (Table 1). It can be conjectured that some of these techniques can be adapted or extended, and used in the context of cyber-physical products. For instance, the features-based approaches can in principle be redefined to address various kinds or forms of features such as functional features, implementation features, installation features, and behavioural features. These kinds of features can then be considered collectively as the basis for predictions or assessments. There have obviously been some successful applications of the existing techniques e.g., in product development organizations and in financial markets. However, apparently some of these techniques are to some extent limited for different reasons. For instance, some of them are based on subjective criteria while others depend on the quality of the available historical data. The techniques that depend on historical data are generally only as good as the data input into the process, and also as good as e.g., the queries used or questions asked. It is also important to note that proper use of these sorts of techniques requires investment of significant time and resources, for instance, in updating the databases or spreadsheets.

Furthermore, since both parametric modelling and forecasting techniques rely on the availability of

Table 1 Summary of forecasting techniques and underlying principles (TP – traditional products; AP - autonomous products; CPS – cyber-physical systems; √ stands for ‘ is used’; + stands for ‘can be used’, -/+ = stands for ‘a fair chance to be reused’; - stands for ‘a small chance to be reused’).

Technique	**Underlying principles**	**Algorithmic/non-algorithmic models used**	**What is predicted ?**	**Application**		
				TP	AP	CPSs
Analogy – see e.g., [23]	Comparison of data of similar projects	Case-based Reasoning (CBR), regression	Cost	√	√	+
Expert judgment – see e.g., [20]	Based on past prediction experience	Fuzzy Logic (FL), Neural Networks (NN), and Case Based Reasoning (CBR)	Cost	√	√	+
Parametric cost modeling – see e.g., [20]	Historical data used as the basis for creating cost function	Regression, Neural networks	Cost	√	√	- /+
Time-series forecasting – see e.g., [1]	Data gathered over time & analyzed	Neural Networks	Plan/ future patterns	√	√	- /+
Scenario writing – see e.g., [9]	Criteria used to generate different prediction scenarios	None	Plan	√	√	+
Delphi technique – see e.g., [12]	Questioning, compilation and re-questioning by using a questionnaire	Rely on a panel of experts	Plan	√	√	+
Subjective forecasting – see e.g., [3]	Brainstorming techniques applied to generate ideas	None	Plan	√	√	+
Bayesian forecasting – see e.g., [7]	Subset of the unknown quantities are taken to be future values	Bayesian approach	Likely course of future events	√	√	- /+
Analytic hierarchy process – (AHP) – see e.g., [28]	Building a hierarchy and systematically evaluation its elements by comparing based on concrete data	Fuzzy Logic, Linear Programming, Quality Function Deployment,	forecasting demand, exchange rate, etc.	√	√	+
Model-based forecasting – see e.g., [21]	Mathematical model	Regression,	Future patterns	√	√	- /+

parametric prediction models, they are cannot be used to predict cost or functional performance in the fuzzy-front end of the processes of development of completely new products. This is also true for all other techniques that involve extrapolation of data that is tied to actual product models such as feature based costing. All in all, as explained in the following section, the challenges faced in this work are unique and need dedicated solutions. We argue in this article that due to peculiarities of CPPs, dedicated techniques are needed to assess and predict functional performance and relevance, as well as cost implications of these products. Meanwhile, we also recognise that while no technique can help the designers and engineers to envisage the future of the imagined product with complete certainty, forecasting techniques remain essential for predicting forward prospects with varying degrees of accuracy depending on the data and processes used.

4. CHALLENGES FACED AND CONCEPTUAL SOLUTIONS

The challenges faced in predicting costs, performance or other future patterns of products or systems differ depending on the nature of the product or system in question. More precisely, challenges arise in several ways, e.g., due to: (a) product or system complexity, i.e. whether the product or system is complex or not complex, where complexity may manifest itself in multiple forms, such as functional, structural, computational, technological, cognitive, application or usage complexity; (b) functional and structural linearity of the product or system, i.e., whether the product or system is linear or non-linear[1], (c) physical presence of the product or system, i.e., whether the product is tangible or intangible, and (d) if the product or system is centralized and decentralised, i.e. how the product or system operates or provides service. The considerations and challenges faced in forecasting may also differ from one product or system to another depending on the *technologies used* to build them (e.g. as electronic, mechatronics, electrical, or mechanical products or systems); the *processes* by which the product or system is developed and build; *application domain* of the product or system (e.g., food products, media products or systems, medical equipment or systems, sport products or systems, and so forth), and even depending on the *purpose* that the product or system in question serve and how the product or system is used (e.g., consumer product or system, service providing products or system, and so forth).

The problem underscored and addressed in the research presented in this paper and a possible way forward can be described as follows. Neither the *elements level* attributes or features nor the entire *system-level* attributes or features of CPPs are known at the fuzzy front-end of the product development process. Therefore, we face a circular reasoning challenge and to a degree somewhat of logical fallacy. From the unknown *elements-level* features, we should be able to come up with the unknown *system-level* features (e.g., for feasibility or cost analysis and prediction purposes). But this is simply impossible as there is lack of knowledge about the elements, and therefore no inductive reasoning about how the whole system will be like can be made. In practice, we first need to make assumptions about the elements of the system and their attributes or features, and then we can reason with them towards the whole (i.e., the entire system). We have to linearize this logic, because the assumptions are not supposed to change. Otherwise, there would be a problem in building up the entire product or system, which would require knowledge, not only about what can be assumed regarding the elements of the product or system, but also about what emerges in the product or system when the elements interact and/or work under certain operational conditions.

Another potential snag is that the elements of a CPP can be of hardware, software and/or cyber-ware nature. This is not only a variety issue, but also a heterogeneity issue (i.e., heterogeneous set of attributes that need to be taken into consideration when reasoning about entire *system-level* characteristics). In simple words, software may not be suitable for hardware due to its foreseeable complexity. We hypothesize that the sought after reasoning model (scheme) should incorporate some sort of abstraction mechanism. So far so good, but the real question is then - how can this be done? And what the reference scheme can do for us? To this end, there are two forerunning questions: (i) how to figure out what are the aspects, and e.g., what weight

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[1] The linear behaviours of products or systems are due to functional features or components that satisfy the superposition principle (i.e., the net response at a given place and time caused by two or more stimuli is the sum of the responses which would have been caused by each stimulus individually), and generate outputs that are directly related or proportional to inputs. In contrast to linear products or systems, non-linear products or systems do not fulfil these conditions.

should be assigned to the aspects for the forecasting task at hand?, and (ii) how can we stack together the criteria that should be applied in assessing or forecasting a particular CPP concept to determine how functionally and economically feasible it is. Probably, we need multiple sub schemes (that ought to appear in integration) to address these issues. That is, first, we have to come up with the ‘aspects’ and the ‘criteria’ sub schemes. The question then is: How can these schemes be developed? Can these schemes be developed based on the requirements for a CPP? This was one of the subjects of investigation in the work presented in this paper.

The goal of our overall research is therefore to come up with an effective approach for assessing and forecasting functional performance and cost implications of various categories of CPPs early on - in the fuzzy front-end of their development processes. In the fuzzy front-end, the requirements for the product or system, and the wishes of the customer are not yet fully known. Therefore, the challenge is how to come up with a sound basis for making predictions. A designer or an engineer often is in a dilemma over how to tackle the forecasting challenges. What is needed is an effective forecasting model that can provide reliable predictions based on the available data and knowledge. In principle, quality and accuracy of predictions depend on (i) the process used, and on (ii) the available data or information. It follows that the only information that can be used to provide quality and accurate predictions at the fuzzy-front end phase of the product development process are the initial ideas (views) and the preliminary requirements for the cyber-physical product or system. Other similar dedicated models can also be developed and used as the basis for predicting functional performance and cost implications in the subsequent stages of the product development process of conceptualization and detail design (Figure 2). In essence, forecasts (and forecasting models) evolve as the product development processes progress, and as new product information continue to emerge. In other words, the data or the information items required in forecasting models naturally differ in various stages of the product or system development processes. This data or information is derived from the descriptions of the products or systems at various development stages in which predictions are made.

5. DERIVATION OF ASSESSMENT AND FORECASTING ASPECTS AND CRITERIA

In this Section, we introduce a reference scheme for systematic derivation of the aspects and criteria for assessing and forecasting functional performance and cost implications of CPPs. The aspects and criteria derived according to this scheme can be used by designers and engineers in the early stages of the product development process. The proposed scheme is built based on the general understanding derived from the literature that a cyber-physical product or system blends naturally intended functions and some additional augmented cyber functions. In other words, the latter essentially arguments the former, and it can be the basis of a new basic function altogether. A system providing the functionality implied by combining natural and augmenting functions will have a set of implementation or manifestation of features e.g., in the form of physical components, software argents or networking tools to enable the CPP to function as it is expected, to

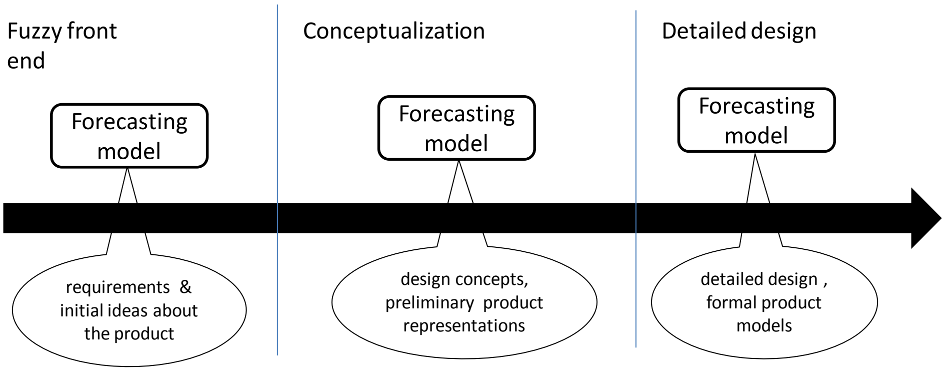

Figure 2 Evolutionary model-based (EMB) prediction concept.

behave as intended, and to provide the expected kinds and levels of service. These system features can be sorted into two broad categories, i.e. (a) classical paradigmatic cyber-physical features (f^P), and (b) basic product or system manifestation features (f_{MF_k}). The former can further be subcategorised as (i) low-end classical paradigmatic cyber-physical features (${}^P f_{LE_i}$), and (ii) high-end classical paradigmatic cyber-physical features (${}^P f_{HE_j}$). Various low-end and high-end manifestations of classical paradigmatic cyber-physical features can be identified. Table 2 shows examples of possible manifestation of low-end and high-end paradigmatic features. A manifestation of a classical paradigmatic cyber-physical feature determines the performance and the capabilities that a particular CPP has. Therefore, knowing the required kinds of classical paradigmatic cyber-physical manifestations in a product is an important prerequisite in predicting how the eventual CPP will perform. Certain basic manifestation features can be integrated into a CPP to meet the requirements and according to the viewpoints (of the stakeholders, including the designers) about the product known at the beginning of the design process, as well as based on those that emerge during the development interval. In case of a CPP with high-end performance characteristics such as self-adaptation capability, the features may change according to the augmentation needs. However, we did not consider these kinds of systems in our research. We only dealt with the system features defined by standard fixed (regular) design requirements and viewpoint of the product's stakeholders. Based on this understanding, the features incorporated in a CPP can formally be defined by using the Equation (1) below.

$$f^P :\Leftrightarrow (\{{}^P f_{HE_i}\} \vee \{{}^P f_{LE_j}\}) \cup \{f_{MF_k}\} \qquad (1)$$

whereby { ${}^P f_{LE_i}$ } with *i= (1, 2 ….. l)* are the low-end classical paradigmatic cyber-physical features, { ${}^P f_{HE_j}$ } with *(j=1, 2 ….. m)* are the high-end classical paradigmatic cyber-physical features; and { f_{MF_k} } with *(k=1, 2 ….. n)* are basic product or system manifestation features. f^P stands for combined set of features in a CPP.

Therefore, according to Equation (1), a product or system can be made by augmenting a certain set of features or entities, { ${}^P f_{LE_i}$ }, which makes the eventual CPP to be of low-end cyber-physical manifestation. In this case, the product or system essentially consists of a set of low-end implementations of classical paradigmatic cyber-physical features (${}^P f_{LE_i}$) and basic product or system manifestation features (f_{MF_k}), i.e.

$$f^{LE} :\Leftrightarrow \{{}^P f_{LE_i}\} \cup \{f_{MF_k}\} \qquad (2)$$

Similarly, a product can be made by augmenting a certain set of features or entities, { ${}^P f_{HE_j}$ }, which makes the eventual CPP to be of high-end cyber-physical manifestation. This can formally be expressed as a direct sum or combination of the basic manifestation features { f_{MF_k} } with high-end cyber-physical paradigmatic features { ${}^P f_{HE_j}$ }, i.e.

$$f^{HE} :\Leftrightarrow \{{}^P f_{HE_i}\} \cup \{f_{MF_k}\} \qquad (3)$$

And a fully-fledged contemporary *cyber-physical product (CPP)* or system, f^{CPP}, consists of a set of features, that are direct sums or combinations of high-end cyber-physical paradigmatic features { ${}^P f_{HE_j}$ } or low-end cyber-physical paradigmatic features { ${}^P f_{LE_i}$ }; and basic manifestation features { f_{MF_k} }, i.e.

$$f^{CPP} :\Leftrightarrow (\{{}^P f_{HE_i}\} \vee \{{}^P f_{LE_j}\}) \cup \{f_{MF_k}\} \qquad (4)$$

In other words, { f_{MF_k} } features can be combined to form a product or system with the required classical basic functions whilst ${}^P f_{LE_i}$, ${}^P f_{HE_j}$, and f_{MF_k} features can be blended in several ways to form a cyber-physical product or system with the emblematic defining functional and operational characteristics such as feedback and control capability, as well as self-adaptation and evolution capability. So, in theory, the incorporation of { f_{MF_k} } features makes the product to the secure basic functional characteristics of a traditional product or system while the augmentation of { ${}^P f_{LE_i}$ } and {

$^{P}f_{HE_j}$ } features in addition to { f_{MF_k} } features brings into the product or system the expected functional qualities of CPPs such as the ability to evolve or the ability to adapt through self-organisation or optimization of the functions to perform tasks more effectively.

Figure 3 shows the proposed reference scheme for deriving aspects and criteria for assessing and forecasting functional performance and cost implications of cyber-physical products or systems. Under the proposed scheme, features are the starting points in deriving the aspects and criteria. According to this scheme, the basic functions of a CPP can be identified by taking into consideration various viewpoints $\{\phi\}$ and technical constraints $\{\rho\}$. And cyber-physical paradigmatic features ^{P}f (i.e., low-end $\{^{P}f_{LE}\}$ or high-end $\{^{P}f_{HE}\}$ features) can then be augmented as required. Based on this refined understanding, features of CPPs can formally be classified as described below:

- $\{^{P}f\}$ include all physical, cyber, and/or software manifestations that enable the execution of the classical computational, networking, and physical operations of the product, i.e.

$$\{^{P}f_{LE}\}\cup\{^{P}f_{HE}\}\supseteq {}^{P}f \qquad (5)$$

- $\{f_{MF_k}\}$ comprise all basic features and elements of the product or system implemented to meet the viewpoints $\{\phi\}$ and to comply with technical constraints $\{\rho\}$ for the product or system, i.e.,

$$\{\phi\}\cup\{\rho\}\supseteq f_{MF} \qquad (6)$$

Each of these features can be *implemented or built* and *installed*, and the realized product or system will subsequently *operate* and *behave* in a certain manner. For each of these four life-cycle aspects (implement, install, operate, behave), the associated cost drivers and constraints as well as the performance indicators and criteria can be specified. As stated earlier, technical constraints $\{\rho\}$ and viewpoints $\{\phi\}$ of stakeholders are vehicles through which the basic functions of a CPP can be implemented, installed and put to use (i.e., operated and behave as expected).

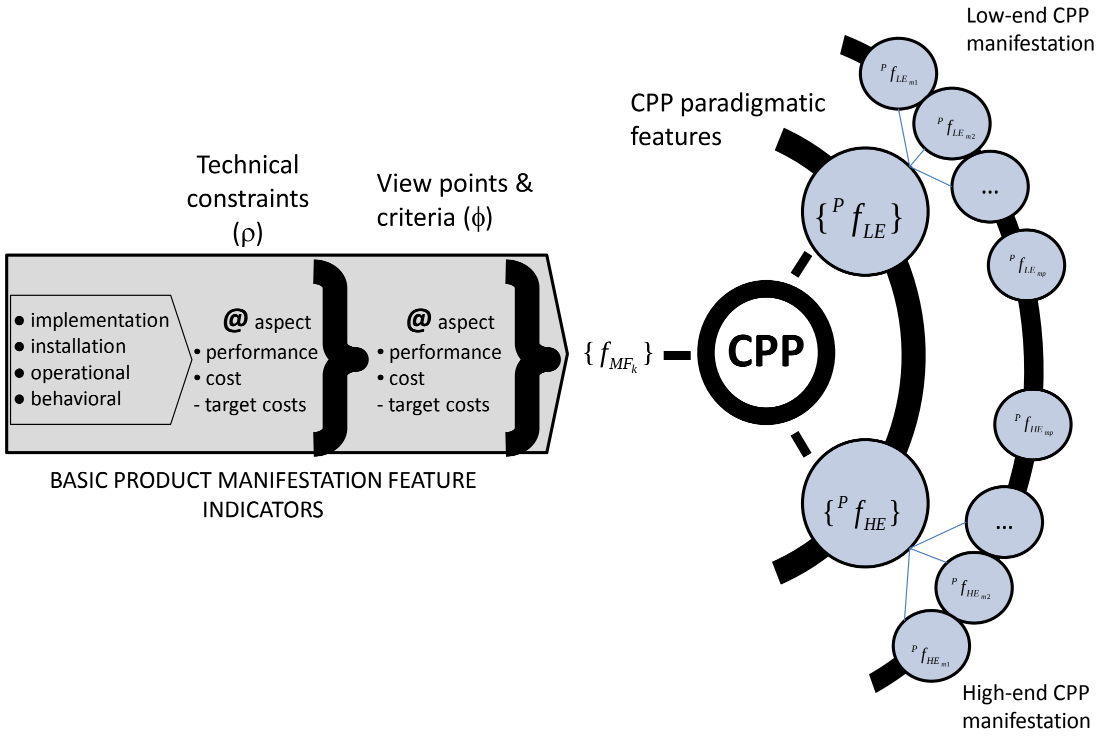

Figure 3. Proposed reference scheme for deriving aspects and criteria for assessing and forecasting functional performance and cost implications of cyber-physical products or systems.

The requirements that describe a CPP as well as the viewpoints of stakeholders must be handled concurrently and synergistically; and their combined institutionalization results into the intended operations, effects, actions and performances of a CPP. In other words, technical constraints and viewpoints specification is a way to describe the kinds of operations, implementations, installations and behaviours that the imagined CPP will have or be associated with (and therefore give a clue about the expected performance of the CPP). These technical constraints and viewpoints can also be clustered in several ways, e.g., according to the abstracted generic functions of CPSs (see e.g. [11]) as e.g., power supply, human interfaces, signal transmitting, information exploring, ambient sensing, reasoning-related technical constraints or viewpoints). The institutionalizations of technical constraints and viewpoints also have cost implications during e.g., production, installation and operation of a CPP. Therefore, technical constraints and viewpoints statements can be formulated early on and used to conceptualize and to figure out e.g., the anticipated way of implementation, installation, or operation, as well as to preview the behaviour of a CPP. This will allow designers and engineers to eventually assess the likely performance and cost of the imagined CPP. Therefore, prediction of cost implications and performance can also be made based on the knowledge of requirements that describes a cyber-physical product or system as well as on the viewpoints of the stakeholders. *Target costs* can be the yardsticks in determining if cost constraints will be met.

In summary, as stated earlier, the aspects and criteria, as well as the cost drivers originate from knowledge of the paradigmatic and basic manifestation features of a CPP. A cyber-physical product or system can have a large number of features (for execution of basic tasks, as well as for execution of cyber-physical functions such as self-adaptation or evolution); and each feature has performance related implications as well as cost implications during production (or implementation), installation and use (or operation). Therefore, the proposed reference scheme provides a framework for deriving comprehensive sets of aspects and criteria for assessing and predicting the implications of incorporating classical cyber-physical paradigmatic features $\{{}^{P}f_i\}$ and basic product manifestation features $\{f_{MF_k}\}$. In theory, the implications of basic product features $\{f_{MF_k}\}$ can be assessed and predicted based on the prevailing forecasting methods. Some of these methods have been discussed in Section 3. Certain specific aspects and criteria should be added to the existing aspects and criteria to assess and predict the implications of augmenting a product or system with ${}^{P}f_i$. The proposed reference scheme is summative - in the sense that the criteria used to assess the functional performance and the cost implications of a product with certain particular basic features can be adopted and reused in entirety to assess a cyber-physical product or system with the same features.

From a practical point of view, the proposed reference scheme requires that statements describing the performance (i.e., operation and behaviour) for the identified categories of features, i.e., both $\{{}^{P}f_i\}$ and f_{MF_k} must be formulated and the cost drivers (e.g., implementation, installation, energy use, and so forth) as well as the target costs must also be specified. These statements are in effect the information items (inputs) needed in the prediction models in the early stages of the CPP development process. These information items can also be used as the basis for conceptualizing and designing a CPP in the subsequent stages; and the resulting conceptualized or abstractly modelled CPP can then be assessed and its performance or cost predicted (i.e., in practice, based on the stated performance or cost drivers, the envisaged functionality, product or system can abstractly be represented mentally or formally and analysed to predict its performance or cost). In other words, these statements define the required functional and operational features of a CPP. And these statements are the basis for abstract modelling of the imagined features of the CPP.

6. IMPLEMENTATION ISSUES

Based on the analysis presented in Section 5, it follows that a tool for deriving the aspects and the criteria for assessing and forecasting functional performance and cost implications of CPPs can be built around the following six core tenets:

- Aspects and criteria for assessing and predicting performance and cost implications of a cyber-physical product or system originate from the viewpoints $\{\phi\}$ and technical constraints $\{\rho\}$ (i.e., operational, behavioural, implementation, and installation viewpoints and technical constraints) as well as from knowledge of cyber-physical pragmatic features $\{{}^{P}f_i\}$ that make up a CPP.

- The viewpoints $\{\phi\}$ and technical constraints $\{\rho\}$ can be clustered according to a selected abstracted generic functions of a CPP (e.g., those presented in [11]).
- The implications of incorporating the basic product manifestation features $\{f_{MF_k}\}$ can be predicted based on the prevailing forecasting techniques (the techniques that can possibly be adapted and used are summarized in Table 1 and have been discussed in Section 4. Examples of the appealing underlying algorithms, procedures or processes that could be used include case-based reasoning, neural networks, and fuzzy analytic hierarchy process).
- New aspects and criteria should be added to the existing aspects and criteria in assessing and predicting the consequences of incorporating classical cyber-physical paradigmatic features $\{{}^{P}f_n\}$ into a product or system.
- The proposed aspects and criteria derivation reference scheme (refer to Figure 3 and to Equations 1-6) is the basis for elicitation of the aspects and criteria.
- Essentially, $\{f_{MF_k}\}$ related aspects and criteria can entirely be adopted when formulating the aspects and criteria for assessing and forecasting the performance and cost implications of comparable traditional products or systems.

Table 2: An example of a list paradigmatic feature manifestations in a CPP.

Paradigmatic feature	Designation (${}^{P}f_n$)	${}^{P}f_{LE_i}$	${}^{P}f_{HE_j}$
Complexity	${}^{P}f_1$	Linearly complex	Non-linearly complex
Adaptability	${}^{P}f_2$	Self-adapting	Self-evolving
Organization	${}^{P}f_3$	Distributed	Decentralized
Connectivity	${}^{P}f_1$	Permanently networked	Dynamically networked
....	....	....	....
....	${}^{P}f_{n-1}$	....	....
....	${}^{P}f_n$	....	....

A suit of tools to support derivation of the aspects and the criteria for assessing and predicting implications of incorporating ${}^{P}f$ features can be developed based on the above-stated tenets. The idea is to enable users to build comprehensive assessment and forecasting models easily and in a structured way e.g., by simply identifying new aspects and criteria, and integrating them into the relevant existing models. The intention is also that the anticipated tool should make it easier to tackle complexity and allow the users to reuse previous predictions, viewpoints, technical constraints, and assessment criteria. A user interface can be incorporated to make it easy to apply the tools (e.g., to input, edit, delete or add a criterion, viewpoint or any data/information) and to provide at-a-glance understanding for novice users who are unfamiliar with the art and science of forecasting. For instance, users should be able to navigate and review the aspects and the criteria used in past predictions easily and quickly to gain some insight into why and how they were used and also to tailor them accordingly to match the problem at hand.

7. ILLUSTRATION AND PRACTICALITY ISSUES

The proposed reference scheme is generic in the sense that it can be scaled and used in deriving the assessment and forecasting aspects and criteria for various CPPs. In this Section, we illustrate how the aspects and the criteria can be derived. The first step in using the proposed aspects and criteria derivation scheme is to identify the features of the CPP that influence its performance as well as the (initial and operational) costs. The reference scheme has defined three broad categories of features that a typical CPP may encompass, namely, ${}^{P}f_{LE_i}$ and/or ${}^{P}f_{HE_j}$; and f_{MF_k}. The latter (i.e., f_{MF_k}) features determine the basic manifestation characteristics of the product or system. The f_{MF_k} features originate from the viewpoints $\{\phi\}$ of the stakeholders and from 'feature indicating' technical constraints $\{\rho\}$ (i.e., operational, behavioural, implementation, and installation viewpoints and technical constraints), which are developed or formulated in the analysis phase of the CPP development process. Viewpoints $\{\phi\}$ and technical constraints $\{\rho\}$ can be used as the basis for projecting the basic functional performance of the CPP. And for each viewpoint or feature indicator, certain particular threshold values (such as target costs) can also be set and used as assessment criteria. Practically, in the early stages of the CPP development process, certain statements that specify the viewpoints $\{\phi\}$ and define the 'features indicating' technical constraints $\{\rho\}$; which correspond to the identified classes of the basic manifestation features (i.e., essentially the specifications of these features or constraints related to these features) can therefore be formulated. Similarly, cost drivers and target costs (i.e., cost criteria) associated with these features can also be specified and used as the basis for assessing and predicting cost.

Furthermore, $^{P}f_{LE_i}$ and $^{P}f_{HE_j}$ features can be derived from well-known lists of established paradigmatic features of cyber-physical product or systems (some examples of these paradigmatic features are listed in Table 2). The aspects and criteria for assessing functional performance and cost implications of incorporating cyber-physical paradigmatic features can be compiled by the product or system developers at the analysis phase by considering the actual needs for paradigmatic features. Various stakeholders can be involved in this. For a given paradigmatic feature (see Table 2) certain viewpoints (e.g., regarding the product or system's behaviour, capabilities, and so forth) and criteria (e.g., threshold values) can be specified and used in assessments and predictions. For example, for the 'complexity' (i.e., $^{P}f_1$' paradigmatic feature listed in Table 2), operation-related aspects such as the number of elements or components in a CPP, the number of relations among the elements or components, and the kinds of relations with the user all together influence the performance of a CPP and can therefore be used as the basis for making statements about the expected performance of a CPP. Similarly, certain threshold values (i.e., criteria) corresponding to $\{^{P}f_1\}$ can be specified and used in assessments.

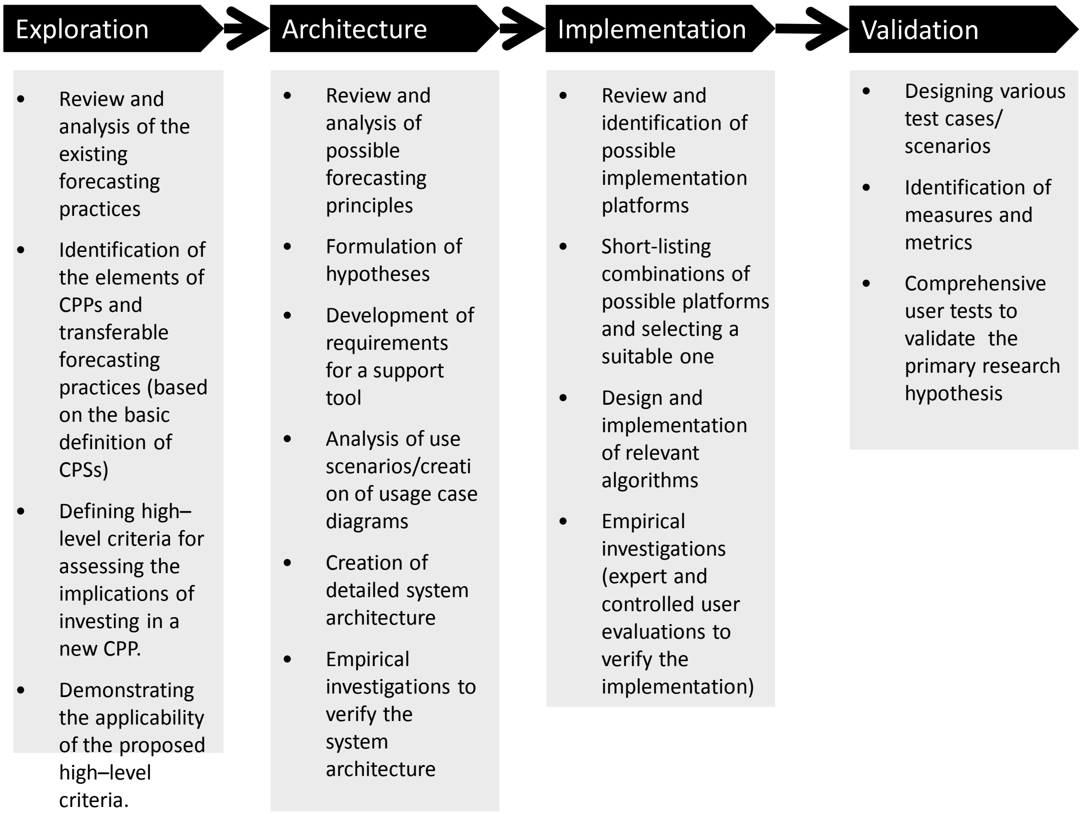

Figure 4. Research cycles.

The $\{f_{MF_k}\}$ and $\{{}^{P}f_i\}$ features are in fact the enablers that constitute complex sets of mechanisms whose combined operations result into the intended effects, actions and performance. A feature or a given combination of features enables the product or system to accomplish certain tailored functions, operations or requests of a user. It should be noted here that depending on the composition of the features, the CPP as a whole may be considered to be of low-end or high-end manifestation. As mentioned earlier, each functional feature of a cyber-physical product or system has performance-related implications as well as cost implications - during production and when in use. Therefore, the product or system performance and offered service will differ depending on the set of features put to use. Also, the costs involved will depend on the features that are actually put to use. Similarly, the initial costs of investing in a CPP will depend on functional features the equipment or the utility actually encompasses.

In summary, we argue that features are the ideal starting points in assessing and forecasting functional performance and cost implications of a CPP. In any prediction process, the sufficiency and completeness of the forecasting model (i.e., the quality of the forecasting *process* itself as well as the reliability of the *data or information items* used, e.g., input into the model) should be given due considerations. For instance, in order to come up with reliable predictions for any CPP at the fuzzy-front end of its development process, predictions should be made: (i) based on the proposed reference scheme (i.e., process), and (ii) the sets of viewpoints, technical constraints, desirable cyber-physical paradigmatic characteristics, and the cost drivers used (i.e., information used) in predictions should be complete and accurate as far as possible. The significance of the proposed reference scheme is that it will allow the designers and engineers to explore knowledge about a novel CPP early on, e.g., to envision how the system will be like, how it will function, and to explore the cost implications of incorporating or excluding various features. This will allow them to come up with meaningful decisions, e.g., on what particular cyber-physical paradigmatic features should be augmented (i.e., low-end vs. high-end).

8. DISCUSSION AND FUTURE WORK

The proposed aspects and criteria derivation reference scheme can be used as the basis for formulating comprehensive sets of aspects and criteria for predicting the likely causes of events for various products or systems in the early development stages. For instance, it can be used in assessing and predicting how a CPP will perform, to predict cost, and to assess other issues associated with the operation of a CPP such as energy consumption, likelihood of failure, failure modes, customizability, and the environmental consequences of augmenting ${}^{P}f_{LE_i}$ or ${}^{P}f_{HE_j}$ features. This will help designers and engineers to make judgements early-on regarding, e.g., technical relevance and viability of various features or components and to know the cost implications of incorporating an additional feature into a CPP.

The importance of the proposed scheme is rather obvious. It is intended to be used as a framework for deriving aspects and criteria. The idea is to institutionalize the scheme by incorporating mechanisms (data source and queries) that would be used to generate general-purpose ‘starting aspects, viewpoints, technical constraints, desirable cyber-physical paradigmatic characteristics, and the criteria’ that can subsequently be refined and used in assessing and forecasting the implications of various basic and paradigmatic features into a CPP. The proposed scheme can quickly capture and avail information about the aspects and the criteria upon which predictions can be made. The scheme allows the users to systematically acquire the information items (i.e., aspects, viewpoints, technical constraints, desirable cyber-physical paradigmatic characteristics, and criteria) needed in forecasting. It is architecturally open - in the sense that various categories of paradigmatic features, viewpoints, technical constraints, aspects and criteria can be added, modified or taken out. In this way, the designer or engineers can tailor the assessments or predictions tasks, e.g., to focus on assessing or predicting certain selected features, or may decide to focus on assessing the fulfilment of a certain set of selected criteria. It can also be extended to include additional paradigmatic features other than the general-purpose ‘template’ clusters of features proposed in this paper (refer to Figure 3 and Equations 1-6). One of the expected advantages of using this scheme is that it will free the designers and engineers from defining the assessment and forecasting aspects and criteria blindly from scratch, as well as from relying on instinctive and ad hoc methods to formulate the assessment and prediction aspects, viewpoints, technical constraints and criteria.

It is also expected to promote reliance on past experiences and reuse of criteria.

It should be noted that in typical practical applications, it is expected that the past experiences will evolve over time and the experiences will continually be refined through continued use and as new information, criteria and experiences are gained. It would therefore be possible to create a library or pool of reusable past criteria, viewpoints, technical constraints, and predictions. The designers and engineers would therefore be able to tap from the existing library or pool e.g., by simply searching the ‘prediction results’ library to find similar or related predictions that would then be tuned to meet the needs of the forecasting assignment at hand. As mentioned earlier, the goal of the work reported in this paper was only to come up with a reference scheme for elicitation of the aspects and criteria for assessing and forecasting the implications of incorporating ${}^{P}f_{LE_i}$ and ${}^{P}f_{HE_j}$ features into a product or system. A suite of tools to support formulation of the aspects, viewpoints, technical constraints and criteria for assessments and predictions still need to be developed. Low-level details of this tool are still far from being settled, and this is one of the subjects for further research and development. Figure 4 shows the main cycles of the overall research (the work reported in this paper is part of the first research cycle). The ‘design inclusive research’ methodology [10 will be used to guide activities in the first three cycles. The research will pass through the indicated four research cycles (i.e., exploration, architectural/detail system design, implementation and validation). Each of these research cycles is essentially a step in the research process that would eventually help us achieve the overall research goals.

9. SUMMARY AND CONCLUSIONS

Many studies have addressed the issues regarding which factors should be considered when assessing and forecasting the implications of investing in traditional products. In the work presented in this paper, the focus was on CPPs, which unlike the traditional products: (i) consist of integrated physical, cyber, and software components; (ii) are developed through complex processes that entail producing and assembling these components into a unified synergistically operating product or system; and (iii) pass through combined life cycle processes that physical, software and cyber products or systems also pass through. We argued in this paper that due to the peculiarities of CPPs, new aspects and criteria need to be considered, in addition to those considered in assessing and forecasting functional performance and cost implications of traditional products. The issues and the broad categories of the aspects and criteria to be considered in assessing and forecasting functional performance and cost implications of CPPs have been specified. This has been achieved, on the one hand, by carrying out a literature review, and, on the other hand, through analysis of features of CPPs. The considerations that need to be taken in formulating a model for assessing and forecasting functional performance and cost implications of CPPs have been structured and represented in a form of a unified general-purpose aspects, viewpoints, technical constraints and criteria formulation reference scheme. This scheme can be adapted and applied in elicitation of aspects, viewpoints, technical constraints and criteria that can be applied in various assessment and prediction processes, e.g., in prediction of the affordability of a CPP, quality, or impact of the eventual CPP on the environment. The scheme can be implemented and institutionalized through proven algorithmic procedures or processes such as case-based reasoning, neural networks, and fuzzy analytic hierarchy process. Its structure allows it to be extended and applied in acquisition of the aspects and the criteria that can be used in performing other assessments and forecasting tasks such as risk assessment. To this end, it can be extended and used, e.g., to generate multiple aspects and criteria for identifying the most important cost risks and opportunities.

Future work includes building a tool that meet standard usability requirements such as providing mechanisms to support easy manipulation and derivation of assessment and forecasting aspects and criteria, and graphical visualization of the existing aspects and criteria models for greater detail and understanding; report generation; sharing of assessment and prediction aspects and criteria, and direct integration with other organization’s applications and platforms (e.g., databases and spread sheets). To test its applicability, the reference scheme will be applied in the processes of development of CPPs in acquiring the aspects and criteria for assessing and predicting functional performance and cost implications. The challenges of capturing and reusing the existing knowledge should also be addressed in future research.

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