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Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning

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ABSTRACT

The primary purpose of this paper is to review currently existing cost estimation methods, models, tools and resources applicable to the space sector. While key space sector methods are outlined, a specific focus is placed on hardware cost estimation on a system level, particularly for early mission phases during which specifications and requirements are not yet crystallised, and information is limited. For the space industry, cost engineering within the systems engineering framework is an integral discipline. The cost of any space program now constitutes a stringent design criterion, which must be considered and carefully controlled during the entire program life cycle. A first step to any program budget is a representative cost estimate which usually hinges on a particular estimation approach, or methodology. Therefore appropriate selection of specific cost models, methods and tools is paramount, a difficult task given the highly variable nature, scope as well as scientific and technical requirements applicable to each program. Numerous methods, models and tools exist. However new ways are needed to address very early, pre-Phase 0 cost estimation during the initial program research and establishment phase when system specifications are limited, but the available research budget needs to be established and defined. Due to their specificity, for vehicles such as reusable launchers with a manned capability, a lack of historical data implies that using either the classic heuristic approach such as parametric cost estimation based on underlying CERs, or the analogy approach, is therefore, by definition, limited.

This review identifies prominent cost estimation models applied to the space sector, and their underlying cost driving parameters and factors. Strengths, weaknesses, and suitability to specific mission types and classes are also highlighted. Current approaches which strategically amalgamate various cost estimation strategies both for formulation and validation of an estimate, and techniques

Abbreviations: AA, Amalgamation Approach; AACE, The Association for the Advancement of Cost Engineering through Total Cost Management International; ACE, Advocacy Cost Estimate; ACEIT, Automated Cost Estimating Integrated Tools; *aces*, Advanced Cost Estimating System; ACostE, Association of Cost Engineers; ADCS, Attitude Determination and Control Subsystem; AGE, Aerospace Ground Equipment; AHP, Analytic Hierarchy Process; AMCM, Advanced Missions Cost Model; ASPE, American Society of Professional Estimators; ATLO, Assembly, Test, and Launch Operations; CBS, Cost Breakdown Structure; CE, Cost Estimation; C&DH, Command and Data Handling; CECM, Cost Estimating Cost Model; CEH, Cost Estimating Handbook; CEM, Cost Estimation Method; CER, Cost Estimation Relationship; COCOMO, Constructive Cost Model; COSYSMO, Constructive Systems Engineering Cost Model; COTS, Commercial Off The Shelf; DDT&E, Design, Development, Test & Evaluation; DLR, Deutsches Zentrum für Luft- und Raumfahrt (German Space Centre); EADS, European Aeronautic Defence and Space Company; ESA, European Space Agency; FAA, Federal Aviation Administration; FAR, Federal Acquisition Regulation; GAO, General Accounting Office; GOTS, Government Off The Shelf; HLLV, Heavy Lift Launch Vehicle; HQ, Headquarters; IA&T, Integration, Assembly and Test; ICE, Independent Cost Estimate; ICEC, The International Cost Engineering Council; IOC, Initial Operating Capability; ISPA, International Society of Parametric Analyst; JPL, Jet Propulsion Laboratory; LCC, Life Cycle Cost; LH2, Liquid Hydrogen; LOOS, Launch and Orbital Operations Support; LOX, Liquid Oxygen; LPA, Launches per annum; LVCM, Launch Vehicle Cost Model; MESSOC, Model for Estimating Space Station Operations Costs; MICM, Multi-Variable Instrument Cost Model; MSFC, Marshall Space Flight Centre; MUPE, Minimum Unbiased Percentage Error; NAFCOM, NASA/Air Force Cost Model; NASA, National Aeronautics and Space Administration; NASCOM, NASA Cost Model; NICM, NASA Instrument Cost Model; OHB, Orbitale Hochtechnologie Bremen; PAF, Project AIR FORCE; PBS, Product Breakdown Structure; PCEH, Parametric Cost Estimating Handbook; PEI, Parametric Estimating Initiative; PLC, Product Life Cycle; PM, Program Management; PRICE, Parametric Review of Information for Costing and Evaluation; RAND, Research and Development; REDSTAR, Resource Data Storage and Retrieval Library; ROM, Rough Order of Magnitude; SAIC, Science Applications International Corporation; SART, Space Launcher Systems Analysis; SCEA, Society of Cost Estimating and Analysis; SE, Systems Engineering; SEER, Systems Evaluation and Estimation of Resources; SOC, Space Operations Centre; SOCM, Space Operations Cost Model; SSCAG, Space Systems Cost Analysis Group; SVLCM, Spacecraft/Vehicle Level Cost Model; TLC, Technological Life Cycle; TransCost Model, Model for Space Transportation Systems Cost Estimation and Economic Optimization; TT&C, Telemetry, Tracking and Command; USCM, Unmanned Space Vehicle Cost Model; VQ, Vendor Quote; WBS, Work Breakdown Structure

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and/or methods to attain representative and justifiable cost estimates are consequently discussed. Ultimately, the aim of the paper is to establish a baseline for development of a non-commercial, low cost, transparent cost estimation methodology to be applied during very early program research phases at a complete vehicle system level, for largely unprecedented manned launch vehicles in the future. This paper takes the first step to achieving this through the identification, analysis and understanding of established, existing techniques, models, tools and resources relevant within the space sector.

Contents

1. Introduction

Historically, attaining maximum performance has dominated design criteria for space programs and missions with maximising performance mistakenly once seen as being synonymous with minimising weight. This ideology, however, has now been rendered outdated with cost becoming the new design criteria of dominance. In today's competitive environment, limited resources and stringent mission budgets constitute a real monetary barrier for access to space, meaning that cost must be a major consideration within the scope of mission planning and indeed for all management decisions and processes. Therefore cost engineering, the new paradigm for space launch vehicle design [1] is an essential component during the preliminary stages of any space program, as well as consistently and progressively throughout the entire project execution. Cost estimation and cost modelling are the two elements focal to this paper, with the topics being of current, significant interest within industry as seen by the rapid advancements and evolution of the processes [2]. The two components have been classified as being key constituent functions within the overall cost engineering and cost control frameworks [3,4]. In fact conclusions from a cost estimate performed during the early Phase-0/A are often a determining factor for program realisation. Within a research context, and given that research drives progress, a preliminary cost estimate performed at a pre-Phase 0 stage can dictate if a developing program is achievable or not within a stipulated, available budget. An initial cost over-estimate can result in a project not being funded, or non-selection within a competitive bidding context. Conversely, significant cost under-estimation increases the risk of financial loss and program failure by influencing the decision making process associated with budget allocation [2,5]. Hence the need for representative and adequate cost estimation during the very

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early program research, establishment and development phase is obvious. Here it is important to note that a cost estimate is a dynamic value rather than a fixed, static one, and as such, should be reassessed regularly so as to absorb and reflect any new information which becomes available. Early in program planning, available specifications and program details may be limited and the resulting cost estimate would therefore have a higher uncertainty than one made later on during the program life cycle. However at this early stage, a representative cost estimate reflective of all available information and data at the given time can optimally support the project funding and underpin allocation of an adequate initial budget.

Most recently, global, social, economic and political circumstances and events have seen the aerospace industry as a whole evolve significantly, and in part, space access has deviated from its fundamentally scientifically oriented and largely government funded origins. As pointed out by Maryniak [6], governments have been ousted and replaced by markets as the principal engines of technological change. Such political variability and an uncertain financial market have both heralded significant changes and restructure within many international space agencies including America's National Aeronautics and Space Administration (NASA), arguably the most prolific body in the world's organisation and funding of space [7]. Coupled with rapid advancements and improved capabilities and affordability of space technologies, these events have all given rise to the plausibility, design and preliminary implementation of novel concepts such as super- and hypersonic intercontinental passenger travel. Concurrently, space tourism in the form of sub-orbital civilian access is becoming an attainable reality while furthermore the promise of civilian orbital flights is also progressing strongly from its embryonic phases.

Diverse papers, articles and reports have addressed and explored the topics of private commercial space flight and space tourism, their advent, current progress and future industry potential [7–13]. Additionally, well summarised by Crouch [14], numerous surveys and studies to gauge interest and plausibility of a space tourism market have been conducted predominantly in the 1990s across Japan [15,16], the USA [17–19], Germany [20], Canada [19], the United Kingdom [21] and even Australia [22]. More currently, several studies are also being undertaken by various international institutions [23]. Generally speaking, findings suggest that conceptually, a significant proportion of respondents were positively inclined towards the prospect of space travel. While such survey results are more speculative than they are conclusive, the common trends observed were relatively consistent and positive, and are well reflected in the conclusions drawn from a key NASA and Space Transportation Association (STA) General Public Space Travel and Tourism study, which states that "serious national attention should now be given to activities that would enable the expansion of today's terrestrial space tourism businesses…in time, it should become a very important part of…[the] overall commercial and civil space business-program structure" [18].

In recognising and adapting to latter trends, an increasing number of private entities, prominent companies, entrepreneurs, space transport technologists and other proponents have emerged over the past decade targeting the anticipated space market from a commercial perspective [12]. Prolific examples include Sir Richard Branson's Virgin Galactic [24,25], a highly successful synergy of the Virgin Group and Paul Allen and Burt Rutan's Mojave Aerospace Adventures [26], renowned for its prize-winning suborbital SpaceShipOne spaceplane. Undoubtedly, Virgin Galactic has impacted significantly and positively not only on the technological advancement of space technologies, but has also reinvigorated media interest, exposure and consequently public awareness in human space access, crucial elements to substantiate any future business case. Furthermore, other companies actively proving and enhancing the existence of a commercial space market include Space Adventures [27,28], Armadillo Aerospace [29], and Elon Musk's SpaceX, whose key organisational goal is "enabling humanity to become a space-faring civilization" [30]. The latter are all major contributors to recalibrating the interest levels in manned spaceflight through heightening exposure and public awareness, as well as pushing barriers of technology and feasibility through competition, seeking to cost-effectively and rapidly progress manned space travel in the long term, while concurrently capitalising on these initiatives. Until now, much of the activities have focused on sub-orbital flights, while more recently focus has also turned to orbital civilian ventures [11]. In fact Eilingsfeld [31] suggests that growth is limited for suborbital space tourism due to very short times to experience space despite relatively high ticket prices. So in order to enhance the business case, he identifies and proposes three options to prolong the space experience, which are an orbital cruiser, a space hotel or a suborbital spaceplane.

One such particular spaceplane which deviates from a purely space tourism objective, is the SpaceLiner [31–33]. This hypersonic, suborbital vehicle is currently under preliminary investigation within the Space Launcher Systems Analysis (SART) department at the German Aerospace Center, DLR, within context of the FAST20XX framework [34], and aims to revolutionise the space market by marrying an ultra-fast means of point-to-point transportation with the allure of thrill seeking and a strong space tourism component. SpaceLiner has the capabilities to travel from West Europe to Australia in 90 min, an unprecedented speed by today's transportation measures (Fig. 1).

Here, it is interesting and relevant to consider the aspect of cost estimation from another perspective concerning the price range that a typical 'space access consumer' is prepared to potentially incur, and for what calibre and purpose of 'product'. This could include orbital or sub-orbital flights with a tourism or high speed transportation oriented focus. Of course the price to the consumer of each space access endeavour will be closely associated with the total development, manufacture and operations costs for each respective space program itself, with, presumably, incorporation of a certain profit margin within a commercial context. Therefore actual program costs will be directly reflected in the ticket or flight costs borne by the consumer. So within this context, and in part relevant to vehicles such as SpaceLiner, in their paper on reusable hypersonic architectures, Kothari and Webber [11] derive a $500,000 figure for potential orbital space tourism. More generally, however, initial forecasts made by the Futron group [13] indicate that the initial customer cluster will be prepared to pay up to $200,000 for a first ticket to space, while more recent circulating predictions suggest that by as early as 2014, a ticket for suborbital flight is

Fig. 1. Artist's interpretation of SpaceLiner 7 (Courtesy of Hochschule für Angewandte Wissenschaften Hamburg, HAW, Hamburg University of Applied Sciences and IDS Hamburg GmbH).

likely to cost between \$50,000 and \$100,000 [35]. This initially apparent discrepancy can be attributed to lower prices incited by anticipated market competition, and given this phenomenon it is therefore reasonable to expect a growing emergence of public companies competing to make access to space simpler and more affordable in the coming decades [36].

Furthermore fundamental marketing theory of a product life cycle (PLC) can be constructively applied to the case of space access in the form of tourism. PLC describes the expected phases for a given product or service, from its inception, design and development, through to maturity and in some cases, obsolescence [37]. In accordance with fundamental PLC principles, Klepper [39] describes that a general trend can be observed for the evolution of a particular industry, irrespective of the industry itself. Klepper proposes that any interdisciplinary product life cycle can be segmented into three fundamental phases being an early exploratory stage, which can be further split into development and introduction, followed by an intermediate growth and development stage, and finally by product maturity [37]. A PLC is then represented visually as a relation of volume of sales and profits with respect to time during the associated phases. While differences and deviations to a traditional PLC and its phases are recognised and classified in wider literature to reflect the varying nature of a product [38], Peeters [39] suggests that the traditional PLC curve, shown qualitatively in Fig. 2, can be applied directly to the potential civilian space access and tourism industries [37].

Working further with the justifiable scenario that space tourism is an attractive and successfully marketable 'product' [9] and combining this with the trend of increasing volume most prominently seen during the product growth and maturity PLC phases in particular, it is logical to expect launcher production rates to consequentially also increase in the coming decades. In a NASA funded study dedicated to projections of future spacelift systems conducted by the Aerospace Corporation, Johnson and Smith [42] conclude that in order to achieve a one or two order of magnitude reduction in cost, flight rates must significantly increase compared to the Shuttle [41]. For a 10 × cost reduction, 48 flights per year are proposed, and 700 flights per year for a cost reduction of 100 ×. Combining a foreseen increase in launch vehicle demand with an increase in flights, should incite technological enhancements in spacecraft hardware reusability, which at present is fairly limited, in particular for launcher vehicles with manned capabilities. Currently, the only projects comparable for this category of space vehicles are the Space Shuttle fleet, which was only semi-reusable [42], and the Russian Buran orbital vehicle, which performed just one unmanned flight before the program was cancelled due to a mix of political influences and lack of funding [43]. Consequently, higher launch rates should drive launch costs and overall space access costs down, requiring

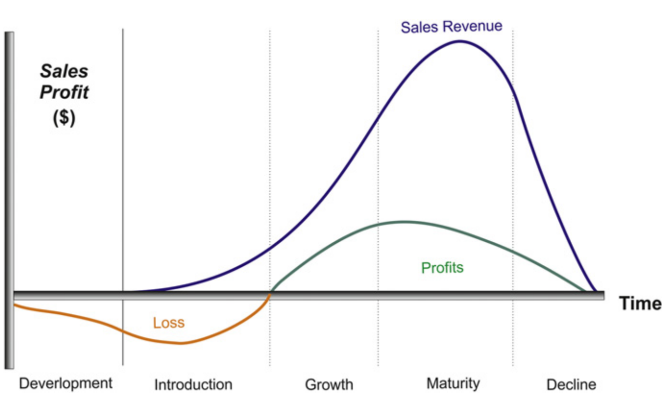

Fig. 2. Qualitative traditional PLC curve potentially applicable to civilian space access industry [37,40].

existing cost models to be recalibrated to facilitate the change. As an example, recent suggestions have implied that the SpaceX fleet of Falcon 9 vehicles "break the NASA/Air Force Cost Model NAFCOM" [44]. So with the recently transpired and justifiably foreseen advancements to space access through the advent of commercial space travel spurred on by current it is essential for cost estimators and experts to keep abreast of the technological changes and have the capability to obtain indicative, relevant and justifiable estimates despite implementation of novel, unprecedented technologies furthermore integrated within new company structures.

Returning back from the costs of applications to the costs of the space vehicles and launchers themselves, to foster and accommodate for such progressive trends within the space sector, stringent and consistently applied cost engineering principles and practices are key to ensure that estimated costs for new, unprecedented programs are representative, justifiable or at the least indicative of expected costs while being reflective of all available inputs and information at the time. As mentioned previously, a cost estimate is a dynamic, constantly varying figure. So while it is impossible to predict exact program costs, consistently applying certain principles, practices and methods, like revising cost estimates at regular interval throughout the program life cycle to incorporate any changes and reflect new information, supports budgeting decisions and maximally assists in avoiding significant, unexpected budget blow-outs [2]. Or if exceeded, helps to ensure that the discrepancy between the existing dynamic estimate, the available allocated budget and the actual cost is minimised. Furthermore, at various program phases the amount of defined information increases as program specifications and requirements crystallise. Here, it is important to identify the most appropriate cost estimation approach at each phase from a diverse selection of cost estimation methods, models and techniques which will be reviewed within this paper.

Numerous excellent resources exist which list and describe general and specific cost estimation methods, models and tools applicable to the space sector. Actually, many of the most extensive documents have been lengthy government funded projects and studies, a fact which only emphasises the importance of the topic within industry. In 1977 The RAND Corporation released a comprehensive study under Project AIR FORCE aimed at listing and assessing the validity of parametric spacecraft cost estimation methods for current and future applications with a decreased focus on system mass, while stressing the importance of concurrent utility of human logic and reasoning during cost model use and application [45]. Consequently, another two in-depth RAND studies into shortcomings of cost estimation methods were released in 2008 [46,47]. In the RAND document which addresses cost estimation of space systems within the Air Force Space and Missile Systems Centre (SMC), Younossi et al. [47] incorporated past lessons learnt, while providing future recommendations for improving the processes, methods, tools and resources based on the study's findings. The second, document by Fox et al. [48] is a dedicated handbook reference describing guidelines and metrics needed to review costs associated with space acquisition programs. Both documents list and contain descriptions of some key cost estimation models, such as the Unmanned Space Vehicle Cost Model [49] (USCM), the NASA/Airforce Cost Model (NAFCOM) [50,51] and Small Satellite Cost Model [52]. More specifically, Meisl [53] described the cost estimating techniques especially for early program phases, while more recently, Curran et al. [54] provide an in-depth look on aerospace engineering cost modelling. Other documents, such as NASA's Cost Estimating Handbook [55–57] and the online DoD Parametric Cost Estimating Handbook [58] also offer their own lists of various industry-relevant cost estimation tools and methods. Depending on the source, the scope of these lists is typically broad, covering many specific estimation methods for mission hardware and software, development, operations, management and risk analysis amongst others, but usually with limited, brief descriptions per entry. Alternatively, the literature will focus on a very narrow range of select models and methods, while omitting key others.

This paper seeks to provide a niche, robust summary for the main cost estimation methods, approaches and resources applied within the space sector for space hardware, with key existing commercial off the shelf (COTS) and government off the shelf (GOTS) tools and software products also discussed. Many of the commercially available products feature classified databases and have associated annual license fees. They are therefore not deemed focal to very early program phases where research into program development is still ongoing, specifications are not yet clearly defined, but a cost estimate for the anticipated program is nevertheless required to proceed further. For completeness sake, these models are, however, included and briefly discussed within the review due to their consistent application in the space industry. Manuals, handbooks and reports directly applicable to space sector cost estimation at a specific complete system level are also outlined, since they are seen as valuable resources for advanced methodology development for reusable launch vehicles. Furthermore, the paper features a hardware focus, and while it is clear that software and associated development, implementation and operations costs are essential for the realisation of every mission, the software-specific cost models are not included within the scope of this paper.

Firstly the relevant cost estimation methodologies applicable to the space sector are outlined and discussed. Consequently, their implementations in key existing models, tools and resources are provided, with each the associated features, factors, benefits, drawbacks and applications detailed and discussed.

2. Cost engineering and cost estimation methods for the space sector

2.1. Role of effective early cost estimation within a cost engineering framework

From labour hours and materials being tediously tallied to obtain crude cost estimates during WWII to advanced models and tools which have been developed and applied today, cost estimation is an integral element of program planning, management, overall system design and the cost engineering framework [54]. While cost estimation and cost engineering are, in their own right, distinct disciplines, the two are intimately related. Cost engineering is a multi-faceted discipline and science which addresses cost estimation and control, business planning and management, profitability analyses and scheduling of major and complex engineering projects through the application of engineering principles [54,59,60]. By applying this definition, cost estimation is therefore a constituent component or subset of the larger cost engineering framework [3,4], and is defined as the process of prediction or forecasting of product or output costs, resulting in an estimate [61]. As previously emphasised, a cost estimate in itself, however, is not a static or deterministic value. On the contrary, it is a living variable which must be progressively updated, revised and readjusted throughout the program life cycle. It is true that an estimate will almost always vary from the final program cost due to unforeseen factors and events which cannot be factored in during formulation of the estimate. Nevertheless careful, realistic budgeting is a crucial first step to underpin future program success, the basis for which is derived from a preliminary program cost estimate. Hence it is logical to state that a justifiable, competent, informed cost estimate reflective of all the data which is available during the early program planning forms a solid foundation for an adequate and supportable program budget [62]. In turn this increases chances for a program's timely and efficient execution and ultimately realisation. An initially excessively high estimate may result in a lost contract award, while an underestimated figure would lead to cost overruns during project implementation [63]. So while there may be preliminary, limited, or insufficient information available regarding configuration, mission or environmental parameters of a mission early during a program, a pronounced need still exists for reasonable, justifiable estimates to be achieved. During such estimates, analyses performed assist in identification of key cost drivers which may be specific to each mission. In 1988, Meisl proposed that a heuristic approach is optimal for application during early program phases where many program parameters, such as configuration, mission and environment, were undefined and unclear. This approach draws upon past experience and knowledge while adjusting for differences between the new and historical data [53]. And within the space sector even today, such a heuristic approach still forms the fundamental backbone of most cost estimation methods and models [2].

Here, during early mission phases, effective schedule management also directly integrates into the cost estimation framework, since the two are directly interdependent. It is clear that time delays result in increased costs not factored for in an initial cost estimate, and therefore in cost overruns. With supporting processes and practices in place aiming to optimise available resources, facilities, funds and materials, careful and strategic schedule definition and management, both essential elements within cost engineering, determine the success of a program [5]. The ultimate objective is to meet project deadlines and achieve cost targets while successfully attaining the required technical performance.

Overall, however, essentially three key elements can be identified to accommodate for effective cost estimation practice [53]. The most challenging includes access to reliable, detailed input data, as well as the appropriate mix of effective tools, methods and models to perform the estimate. The latter must be consistent with program phase and system definition at the time of the estimate [53]. Finally, a skilled cost estimator with sufficient knowledge and estimating experience is required to bring all the elements successfully together. The estimator is then responsible for amassing the right data, polling adequate information, asking the right questions and ultimately translating the latter into model inputs [53]. If any single part of this process chain is omitted, then a cost estimate is unlikely to be indicative of program cost, and therefore not useful.

This paper focuses specifically on one of the three elements, being the cost models, methods and tools aspects. Identification, selection, application and sometimes development of cost estimating models, methods and tools within the space sector is a difficult task given the highly variable nature, scope as well as scientific and technical requirements applicable to each mission. This decision ultimately hinges on the program phase, the accuracy required, available resources and information and risk analyses, and is the responsibility of the program manager, and subsequently the estimator themselves.

2.2. Cost risk and uncertainty assessment

In addition to careful scheduling, to minimise the likelihood of cost overruns and scheduling delays, the effects of unexpected events must be considered during initialisation of a program. This process is particularly crucial during formulation of a program's initial cost estimate, when a detailed understanding and assessment of potential cost risks is essential. Various facets

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and definitions can be applied to the terms 'risk' and 'uncertainty' within the context of a program and the required or existing cost estimate for that program.

2.2.1. *Risk and uncertainty of unexpected events*

The meaning of the term 'risk' differs subtly yet distinctly from the meaning of 'uncertainty', and this definition is important to establish. Risk addresses the probability of a certain event occurring and its consequent impact on a project, and therefore risk can be in part preempted for and factored in within an estimate. Uncertainty, however, relates to an unforeseen, unexpected event which becomes known only after it has occurred [64]. So while potential risks for a project can be identified, analysed, planned for and managed, the uncertainty element for unexpected costs during project lifetime is impossible to fully address during the early program phase. Furthermore, risk and uncertainty are not mutually exclusive, with the modelling of uncertainty directly translating into risk [58]. Therefore any given project can never be entirely risk-free, although various cost risk quantification analysis methodologies, strategies and approaches exist to address this aspect. While cost risk estimation is an extremely important element within the cost estimation process and cost engineering framework, it is not delved into in great detail within the scope of this paper. Interested readers may refer to the following references for further details on cost risk and uncertainty assessment and management [48,57,58,62,65].

2.2.2. *Uncertainty of cost estimate*

Another type of uncertainty not directly associated with unexpected events arising during a program relates to a formulated cost estimate itself. This uncertainty is associated with the development or implementation and thus usefulness of any cost model underlying the estimate, and includes factors like omission of a key cost driver, data inconsistencies, and model limitations and simplifications due to lack of data [58]. Additionally, this uncertainty also encompasses an estimate's accuracy based on correlation with a program's phases. Normally, early in a program only few specific mission details are available based on which a first cost estimate can be formulated. Therefore due to this often insufficient or incomplete knowledge of parameters, uncertainty around the initial estimate is high. As the program advances through development and into implementation, specifications and mission requirements begin to emerge and crystallise. Concurrently, the initial cost estimate should be reassessed regularly, and in this way the cost uncertainty associated with the first preliminary estimate is reduced with every iteration. It has also been shown that costs are more likely to overrun than under-run [66], with the initial cost estimate baseline generally tending to increase as the program develops. Here, the baseline cost refers to the most likely cost estimate figure assuming no abnormal problems occurring and normal working practice is adhered to. The latter processes and principles are graphically illustrated in Fig. 3 in what is referred to as the cone of uncertainty [66]. The horizontal axis represents project milestones and phases, while the vertical axis indicates estimation uncertainty and variability. While the model is generally applied specifically to software development, the cost concepts described therein can be effectively extended and are relevant beyond the software domain alone.

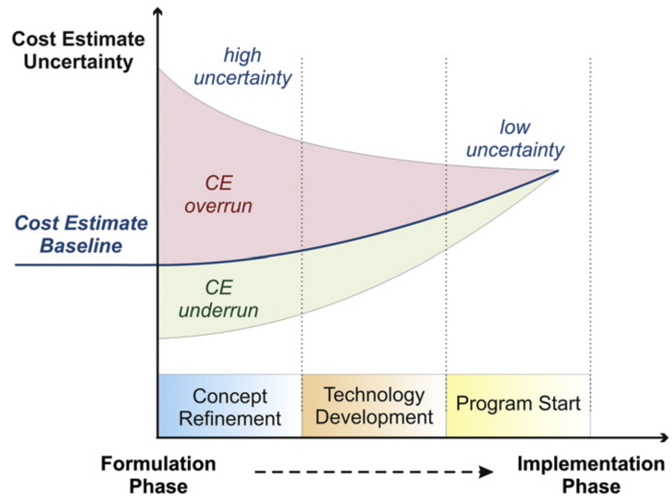

Fig. 3. Cone of uncertainty illustrating estimate uncertainty associated with baseline cost estimates as it is iterated throughout the program phases [62].

2.3. *Diversity of cost estimation within the space sector*

Cost estimation within the space sector must be able to encompass a diverse scope of missions ranging from simple satellites to reusable launch vehicles and manned spacecraft. Each project is then further broken down into its technical system and sub-system deliverable elements as well as organisational components. Therefore at various stages of a program, separate cost estimates are required to address program development and manufacture of both hardware and software, operation costs, life cycle costs (LCC), management and organisation costs. Other cost assessments, such as advocacy and independent cost estimates (ACE and ICEs) are also required, which are separate, although associated with or embedded within the context of an existing LCC estimate [55]. To facilitate for all these cases, proper selection of appropriate estimation methods and tools is vital, since this positively impacts on overall project costs. Many variables and considerations dictate this choice, including available technical definition detail and program phase, the scope of the effort to be costed, allocated resources, availability of historical cost data and program maturity coupled with the cost estimator competency and experience [55]. While it is important to recognise these differences, the methods and processes themselves remain fairly consistent.

To address the diversity for cost estimation purposes, numerous proprietary, dedicated models exist to estimate various aspects of mission costs for both software and hardware. These include cost models for subsystems and space instruments (SICM, NICM, MICM) [48,55,67], systems engineering processes (COSYSMO) [68], operations and processing (SOCM, MESSOC) [69,70,71], as well as ground development and risk assessments (ACEIT, Crystal Ball, @Risk) [55]. Even a model for determining the cost of performing a cost estimate has been addressed [45,72]. This paper, however, specifically focuses on COTS and GOTS cost estimation approaches applicable on a more global system level for an overall space flight project with a hardware focus. The methods described within this paper are normally best suited and particularly necessary and applicable during the initial phases of program development and mission planning.

2.4. *Cost engineering oriented organisations*

The importance of effective, efficient and accurate cost engineering practices, as underpinned by effective cost estimation throughout a program life cycle, is unquestioned. Yet despite this fact, cost estimation methods and practices within industry remain largely undefined, with a lack of understanding stemming from limited education, training and support available to the cost engineering community. It is logical that an ability to control costs directly hinges on closely adhering to set guidelines and learning from previous projects while simultaneously reacting to current circumstances efficiently and effectively [73]. Yet prevailing organisational inconsistencies concerning the absence of formal structure, documentation and processes for cost estimation methods and practices [59] combined with ineffective retention of past experience, knowledge and 'lessons learned' continuously results in inefficient outcomes. And with deadlines and competitive bidding for projects adding time pressure to the compound mix, unstructured, hasty cost estimations result in repeated significant budget overruns, particularly within larger organisations and agencies like the US DoD [74], ESA [75,76], and NASA [77].

These issues and inconsistencies have underpinned the emergence of numerous professional, industry and government cost estimation groups and organisations whose core fundamental philosophies and aims are to promote the standardisation of cost engineering principles within industry. This is done through encouraging effective knowledge management and retention, and pooling available resources to establish and maintain a common basis and standards for cost engineering practice. Amongst others these include the International Society of Parametric Analysts (ISPA) [78], Society of Cost Estimating and Analysis (SCEA) [79], the Space Systems Cost Analysis Group (SSCAG) [80], the Association for the Advancement of Cost Engineering through Total Cost Management (AACE) International [81], American Society of Professional Estimators (ASPE) [82], Association of Cost Engineers (ACostE) [83] and the International Cost Engineering Council (ICEC) [84]. While having a slightly different focus, fundamentally all of these organisations share the common core goal of cooperating and promoting better, more consistent cost engineering principles and cost estimation practices and standards within industry.

2.5. Cost estimation methods

Predominantly, three main, staple cost estimation methods (CEMs) form the backbone of tools applied for cost estimation within the space sector: engineering bottom-up, analogy and parametric approaches. The detailed bottom-up estimation approach encompasses the synonymous techniques of engineering build-up, grassroots or detailed cost estimations. Analogy and parametric cost estimations are part of the top-down methods or statistical approaches and can be classed as gross estimation methods. Expert judgment (EJ), arguably, is another cost estimation approach, although there does not appear to be a clear consensus in literature on whether or not it constitutes an official method [85] despite its widespread application.

Several of the techniques can also be strategically combined to formulate a hybrid estimate. Alternatively, if this is possible, an existing tool or model can be taken and potentially 'tailored' to a particular mission's specifications through manual input or calibration. Given recent dynamic progresses and advancements to space access and technologies with the political environment encouraging commercial space access coupled with the advent of space tourism, it is more important than ever to have the capability to obtain representative cost estimates. Currently, given the promising prospects for commercial launches [37], ultrafast space transportation [32–34] as well as the potential for space tourism [8,9], this applies particularly to launch vehicles with manned capabilities. Yet very limited precedent and consequently very limited data exists for this category of spacecraft, limiting the suitability and application of the most commonly implemented CEMs within the space sector.

The key CEMs currently recognised and utilised within the space sector are concisely summarised below, and their respective attributes provided. Potentially, however, new methods need to be investigated, a process which must begin from recognising and analysing those estimation methods in use today.

2.5.1. Parametric cost estimation

Parametric cost estimation is used prolifically within both industry and government applications, offering a means to economically approach proposals, negotiations or basic program cost assessments which rely on cost or price data and estimation. More specifically, the parametric approach is commonly used within planning and budgeting during acquisition processes [58] with the CEM having official acceptance by the Federal Acquisition Regulation (FAR) for proposal preparation [86]. It is also the foundation of numerous key models and software used for early phase cost estimation of space programs, such as the TransCost Model [87], the USCM [49], and NAFCOM [50,51].

Best applied within early program phases, a top-down approach is assumed since only basic requirements are usually available, while more detailed system and subsystem criteria are not yet established. A series of mathematical relationships called cost estimating relationships (CERs) are then determined based on historical data. CERs seek to relate cost to physical, technical and performance parameters that are known to strongly correlate with program costs. Complexity factors, or specific manually defined user inputs can then be applied to address deviations from underlying CER parameters and a particular mission of interest.

However while it is commonly believed that early mission costing cannot be done effectively in any other way, a difficult aspect of parametric cost estimation is the actual CER formulation itself. A cost model is only as robust and reliable as its underlying database of projects, so database quality and size impose limitations on CER credibility [88]. Significant amounts of time and resources are devoted to the collection of quality raw data, which then usually needs to be adjusted for consistency, or normalised, to make it comparable and compatible with other relative data perhaps from various sources. The challenge lies in obtaining sufficient, representative quantities of cost data, yet alone in finding accurate, relevant and sufficiently detailed numbers and figures. The DoD Parametric Cost Estimating Handbook [58] identifies nine main data sources which include basic accounting records, contracts, cost reports and proposals, historical and technical databases, other information systems and organisations, and functional specialists. Here, a key difficulty concerning access to data arises due to the classified nature of most projects within context of a competitive space industry and environment. This is exactly what often renders the data collection process as the most time-consuming, strenuous and costly aspect for accurate CER formulation and indeed for cost estimation [57]. Even extracting data retrospectively from projects poses challenges relating to contractual and administrative complexity [87]. Furthermore, all developed CER credibility must be verified through comparison and sufficient correlation to existing projects. The interested reader is directed to consult references [58,62,89] for more detailed information about quality data collection, adjustments and normalisation for CER development.

In addition to the challenges of CER formulation, the CERs, once developed, may not be relevant when new technologies or requirements beyond normal boundaries of the underlying CERs are introduced [90], as is exactly the case for manned RLVs. In this respect, assumptions must be made that historical data is representative of future conditions, rendering CERs only effectively applicable to projects similar in nature as the CER data itself. A solution here is to employ an alternative estimation method which can be used as a sanity check, or to combine several approaches if it is possible to segment the cost estimate into constituents which can each be addressed by various approaches.

2.5.2. Engineering build-up estimation

Known synonymously as engineering build-up, bottom-up, grassroots or detailed cost estimation, this very specific analytical approach is generally applied to a mission when all parameters at system and sub-system levels are known and clearly defined. Cost estimations are then performed at the lowest level of detail, and require a breakdown of the overall project into smaller work packages, taking the form of either a Cost Breakdown Structure (CBS) or a Work Breakdown Structure (WBS). The low level cost estimates usually come directly from the engineers and experts performing the designated work, the sum of which then constitutes the overall cost estimate for the program. It is common for labour requirements and non-labour factors, such as material quantities, to be identified and estimated separately, with any additional overhead costs, such as administrative expenses, being concurrently factored in to obtain the total estimate [55].

Therefore engineering build-up is inherently an extremely resource-intensive approach with significant associated costs, as well as time and effort involved. Very careful attention must be paid to the organisation of the WBS and CBS to avoid duplications and omissions of tasks, which would then reflect directly and misleadingly on costs [64].

Inability to quickly adapt to scenario changes or specifications, requirement and design alterations, which frequently arise during early planning phases, is a weakness of this CEM. Given any modifications, new estimates must then be built up anew. So ideally, detailed, advanced and confirmed low level specifications are necessary for application of the engineering build-up method. These are usually not available during the beginning stages for mission planning, which renders the approach unsuitable for application during early project phases.

However if applied during later project phases when sufficient details are available (i.e. Phases A–D), the resulting cost estimate can be extremely accurate since it is unique to the specific industry and application [62]. Credibility is established since the total cost can be broken down into constituent cost elements, providing clear insight into major cost contributors, making elements of the estimate reusable within individual project budgets, and rendering the cost estimate defensible [55]. Insight is also gained into major drivers and contributors to overall cost, which can be useful for program review and analysis, as well as incorporated in future projects as lessons learned.

2.5.3. *Analogy estimation*

Analogy cost estimation relies on an extrapolation based comparison between different precedent or existing efforts which are deemed to be similar or 'analogous' with the item being costed [55]. Intensive analyst judgment is required regarding the similarity of two projects, followed by adjustments made for any differences, such as project size, complexity, team experience or technologies, between them. Although necessary, such judgment is often considered subjective [62]. Application of the method is also limited since identifying a suitable analogue or adequately detailed technical, program and cost data is often an extremely difficult task. If successfully identified, reliance for the comparison is then based on a single data point only. Therefore sufficiently detailed data of the 'compared' system as well as the 'new' system under consideration is essential. The method then hinges on the past experience, knowledge and judgment of the expert regarding consequent adjustments or extrapolations.

Strengths of the analogy CEM include its quick and effective application at any time throughout the various program phases at a minimum cost, since analogy can be applied even before specific program specifications are known. And if a close suitable analogue is found, the resulting estimate is then based on sound factual historical data and is defensible.

Analogy can be further broken down into Loose Analogy (LA) and Close Analogy (CA). LA requires only few 'loosely similar' data points not closely related to new project, and adjusts relevant past broad experience for moderate changes in complexity. CA requires very similar data points from either another program or through technical development studies, and calls upon direct past experience with adjustments made for only minor changes in complexity [90], and is therefore more resource intensive.

2.5.4. *Expert judgment estimation*

Expert judgment (EJ), or expert opinion, is a commonly applied methodology despite being subjective in nature of the assumptions and assessments which are formulated by the estimator based on their own experience and knowledge. It is also a key element within the previously discussed analogy CEM. According to ESA's Engineering Costing Techniques specifications, EJ is deemed to be the fourth cost estimation method [2], then contradictorily as both the backbone and limitation of the analogy approach [88], as knowledge based cognition [91] and simply guessing [92] in other literature. A widespread feeling exists that the EJ approach is particularly intuitive and as such, consequently liable to personal knowledge bias and sensitive to political pressures [85]. Yet while being frequently criticised and often misunderstood by those outside the cost estimating community [59], EJ is nevertheless consistently and extensively used in the generation of cost estimates [2,93]. This approach can be applied throughout all project phases, and can be beneficial when historical data is scarce or unavailable. While gathering a group of experts may require some resources initially, once achieved, EJ requires comparatively minimal effort, time and cost and is often used as a sanity check for CER results where implemented data is significantly beyond the CER data ranges [62]. In fact , other than analogy, various more advanced techniques have been designed with EJ at their core. One example, the Delphi method, relies solely on group expert engineering judgment obtained from several professionals, to provide the cost estimator with latitude in their cost prediction [55]. Another useful approach is the Analytic Hierarchy Process (AHP) which was developed by Dr. Thomas Saaty [94]. AHP decomposes a problem into a hierarchy of specific criteria and alternatives. Expert judgment is then employed to determine and assign specific rankings, or priority scales through pairwise comparisons to the established criteria [95,96], and after some normalisation of the rankings, an overall relative score can be deduced for each option. An advantage of the method is its capability to significantly reduce complex, multi-faceted decisions to a series of simple pairwise comparisons, in this way capturing and reflecting the subjective and objective aspects of a decision [94]. Another strength is the method's applicability to a decision process despite the absence of quantitative ratings, since assessors and experts are always capable of determining which criteria dominate over other criteria within a pairwise comparison context [97]. A recognised weakness of the approach pertains, however, directly to the same weakness as that of the EJ element itself, namely the fact that the expert judgments involved can be inconsistent or prone to knowledge or experience bias. Furthermore, ways to gauge any inconsistency and improve the EJ element of AHP are challenging [97]. Despite this, AHP constitutes a powerful tool for comparisons of alternative design concepts based on both qualitative and quantitative criteria.

2.5.5. *Rough order of magnitude estimation*

The NASA 2002 Cost Estimating Handbook defines the rough order of magnitude (ROM) estimation as one of "four generally accepted estimating methodological approaches" [55]. Also referred to as a vendor quote (VQ), this 'first order' methodology is useful early in mission planning phases to estimate costs either already known from past experience, or readily available based on polling of current industry wide data [90]. Applications of the ROM method for cost estimation include hardware, facilities and

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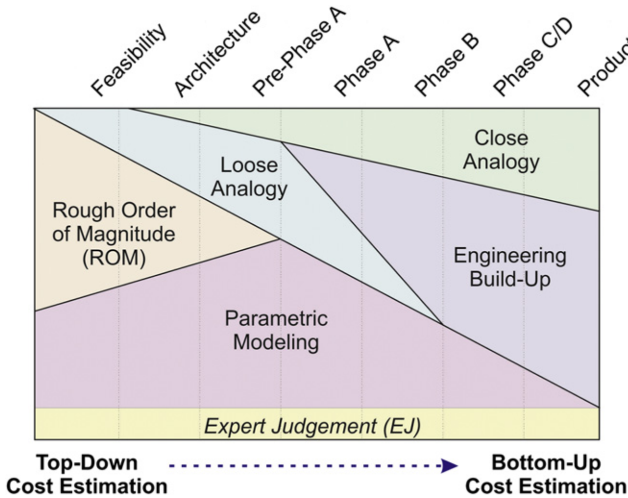

Fig. 4. Qualitative application of CEMs according to project phase [90].

services, usually when a project has not been started and when requirements are not explicitly specified.

2.6. Cost estimation methodology selection

In order to initiate a relevant, indicative and valid cost estimate for a mission, identification of the most appropriate CEM which can most realistically indicate program costs on a case to case basis is essential. While the method by which the cost estimation will be performed is normally decided by the project manager, the responsibility to understand, select and verify the pedigree and applicability of a suitable model which utilises the chosen method, then falls on the estimator and is essential to the accuracy and relevance of the estimate [55].

Throughout the program life cycle, information, the levels of details and sometimes key requirements and specifications relating to the project change. Concurrently with each phase change, it is necessary to reevaluate the cost estimate and update this to incorporate the new information as it becomes available. The various CEMs discussed are to varying degrees appropriate for use during the different program phases. This suitability and adaptability of the different CEMs with respect to time and therefore phase is qualitatively shown in Fig. 4.

3. Cost estimating tools and models

Once a suitable methodology has been defensibly identified, usually, and in accordance with project phase, a tool or model implementing this methodology must then be found. No single model or tool is applicable for all purposes, so numerous options have been developed around the CEM principles previously discussed to address the complex issue of cost estimation within a diverse space sector.

Furthermore, a mission can be broken down into the three clear stages for its life cycle costs concerning all aspects, elements and components. These phases are development, production and operations, and encompass both software, hardware as well as various processes like storage, maintenance, disposal, and support. Therefore to address the different phases, the CEMs discussed in this paper are often adapted and incorporated into numerous, often mission-type specific handbooks, manuals and models, like the TransCost Model [87], and software packages like PRICE System's Solutions Suite [57,98].

A visual representation of respective cost components for each mission phase and associated software and hardware elements is presented in Fig. 5. Various sets of tools, methods and models exist to address the different links, represented by the arrows. The solid arrows pointing to the space hardware element, represent the cost estimation methods and tools specifically considered within the scope of this paper.

Several key COTS and GOTS software packages are available on the market in addition to detailed manuals, handbooks, and other various models, and cost estimators must select the most suitable cost assessment means for a given project. Such choice is, of course, subject to constraints including laws and regulations (such as ITAR [99]) and license and subscription fees for most software packages. The cost estimator must be capable to justify their choice of cost model, as dictated by project purpose, phase and level of design details available [55].

3.1. COTS cost estimation models

While many other excellent tools exist, this section describes six key COTS models commonly used to formulate space sector appropriate cost estimates, as shown in Fig. 6.

Within this context, the NASA COTS definitions will be applied [57], which refers to those commercial models requiring no modifications or maintenance over the product life cycle to meet the needs of the procuring agency.

The TransCost Model, the Unmanned Space Vehicle Cost Model (USCM) and the Aerospace Corporation Small Satellite Cost Model

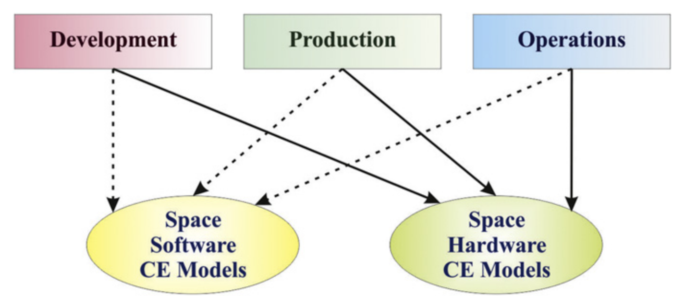

Fig. 5. Interrelation of mission phases with hardware and software CE model categories considered in this paper.

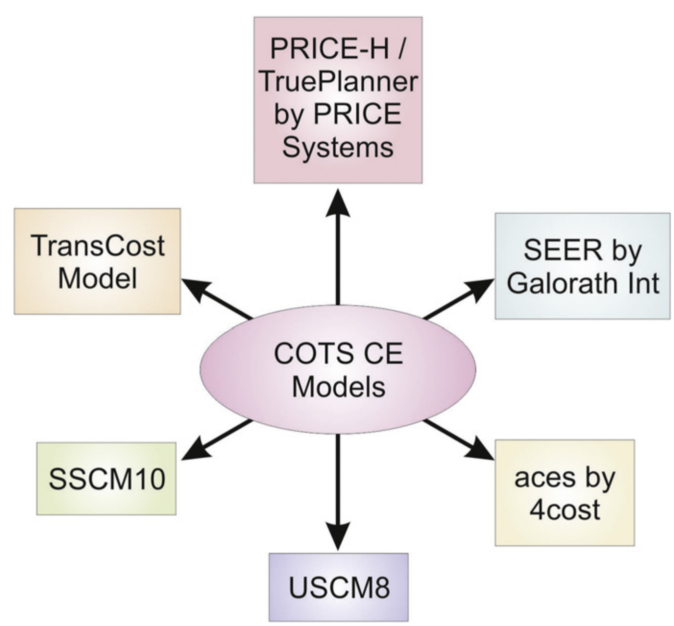

Fig. 6. Scope of reviewed COTS cost estimation models.

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(SSCM) are all available freely, subject to some basic conditions. The remaining listed COTS models and tools, including PRICE Systems Solutions, SEER by Galorath Incorporated and *aces* by 4cost, all require varying annual license fees.

3.1.1. TransCost Model

The TansCost Model for Space Transportation Systems Cost Estimation and Economic Optimization is a dedicated launch vehicle system model encompassing the development, operations and manufacture stages of expendable and reusable launch vehicles. It is therefore of interest within the context of this review. The model itself is integrated into the Handbook of Cost Engineering for Space Transportation Systems. Designed specifically to be applied in the initial conceptual mission design phases, TransCost was an extension of the 1971 dissertation work of Dietrich E. Koelle and is now a very commonly used space transportation cost model within industry [87], perhaps due to its low cost and ready availability, simple handling, and transparent CERs and data which underlie the model.

Conceived initially as a cost engineering tool, TransCost uses the parametric CEM with rudimentary CERs derived from a vehicle and engine database of cost data for European and US space vehicle and engine projects within the 1960–2009 timeframe. Being a dynamic model, both the database and CERs are continuously updated, and the latest model available since October 2010 is TransCost Version 8.1.

The model itself addresses three areas of the launch vehicle life cycle costs, being development, production, and operations costs. Each category is further broken down into sub-categories, each with its own unique respective CERs, which address distinctly identified categories of expendable and reusable vehicles and craft, and include solid propellant boosters, liquid propellant, pressure-fed as well as turbo- and ramjet engines, and crewed capsules and space systems. Different factors underpin each CER, and include vehicle mass, number of launcher stages, number of units produced and expected launch rate. A range of ten complexity factors are then further assigned, which address the impacts of varying technological advancements and quality level, team experience, regional productivity, series production, effects from increased number of participating contractor organisations, subcontractor-ship or government involvement, optimum schedule deviations, and past technical experience. A visual representation of the TransCost Model structure breakdown is presented in Fig. 7.

A particular feature of the model is the use of the 'Work-Year' costing unit, which provides firm cost data transcendent of inconsistencies due to international currency conversion rates and annual inflation fluctuations. TransCost and all constituent CERs are entirely transparent with each CER specified, explained, and all underlying reference projects shown, with accuracy for historic cost data regression stated as being within $\pm 20\%$ of cost data range [87]. The open nature of TransCost also means that it can be easily implemented within various programming environments, such as Excel©.

3.1.2. Unmanned Space Vehicle Cost Model (USCM)

The USCM is a parametric handbook and cost model from the Air Force, with the latest Version 8 released in 2002 providing CERs to facilitate estimation of unmanned, earth-orbiting space vehicles [49] as well as flight hardware, aerospace ground segment, design, development, testing and evaluation and launch and orbital operations support [55]. The freely available USCM8 document features transparent, visible CER equations. Furthermore the rigorous CER development process, which identifies cost driver parameters, relates them to costs and is followed up by validation through comparison with engineering expectations, is described. Based on a NASA, military and commercial satellite database, a particular feature of the model is that CERs at subsystem and component levels are based on the Minimum Unbiased Percentage Error (MUPE) regression technique [49]. Sensitivity analysis (i.e. for inflation and requirement changes), as well as error assessment, are discussed in dedicated chapters. Finally a hypothetical case is presented to demonstrate applicability of the USCM using specific relevant CERs provided within the USCM. Table 1 shows a record of the data point count for each version of the USCM through its development and modification iterations.

3.1.3. Small Satellite Cost Model (SSCM)

The SSCM was developed in 1989 by the Aerospace Corporation [100], and is a parametric model which estimates subsystem and system-level program costs for the development and production of small, newer class C and D Earth-orbiting and planetary spacecraft weighing less than 1000 kg, minus payload. Based on a

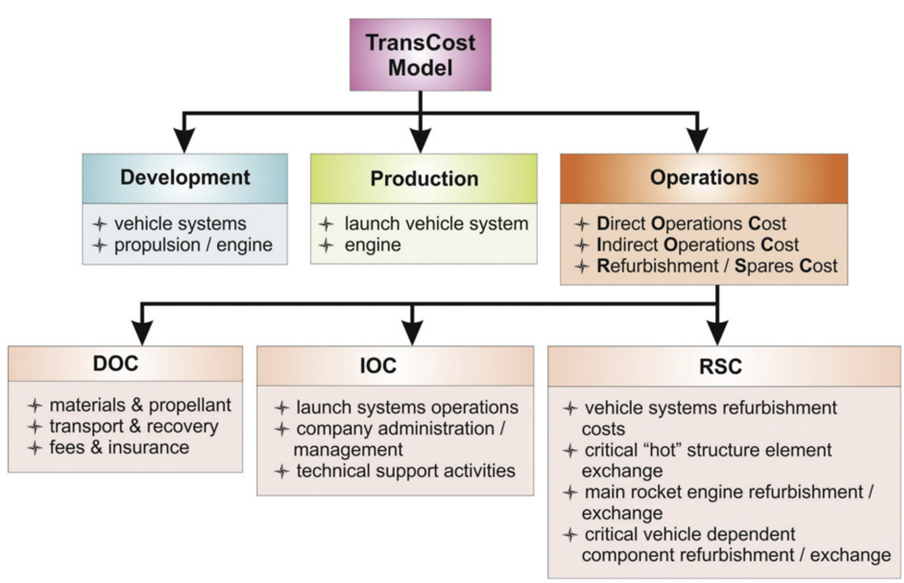

Fig. 7. TransCost Model category structure for CERs and costs.

Table 1
USCM versions data point count [49].

Program type	1st edition	2nd edition	3rd edition	4th edition	5th edition	6th edition	7th edition	8th edition
Military	*5*	*7*	*11*	*11*	*16*	*9*	*19*	*23*
NASA	*6*	*11*	*12*	*13*	*13*	*4*	*4*	*12*
Commercial	*1*	*1*	*2*	*3*	*3*	*3*	*2*	*9*
Total	12	19	25	27	32	16	25	44

transparent database of missions, the SSCM is available at no cost to organisations within the US and abroad subject to Export Control Office review [52]. Operating in Microsoft Excel© the spreadsheet-based graphical interface offers ease of use. Inputs include user defined inflation factors, and notification of inputs which lie outside expected input ranges. The output includes a range cost estimate, which is further segmented into both system and subsystem cost breakdowns.

The SSCM is suitable for application during early development and mission planning stages of a program to allow for easy trades between cost and performance to be made efficiently. The resulting cost estimates are interval rather than point cost estimates, with a cost-risk distribution giving a range of cost estimates and percentiles. CERs underpinning the SSCM are derived from actual costs and technical parameters of small satellite missions, while the database itself incorporates a continually expanding number of small satellites. This ensures that the SSCM properly reflects latest trends in cost-efficiency and technology development. The latest SSCM10 version released in October 2010 is based on 76 as-flown missions with all cost and technical data as provided by the spacecraft bus manufacturers [52].

SSCM estimates project cost based on inputs for subsystems and elements including power, structure, Attitude Determination and Control Subsystem (ADCS), Command and Data Handling (C&DH), thermal, Assembly, Test and Launch Operations (ATLO), Program Management (PM), and System Engineering (SE).

Dedicated CERs also estimate costs for ATLO Integration, Assembly and Test (IA&T) and Launch and Orbital Operations Support (LOOS). The resulting overall cost estimate is therefore segmented into the latter categories.

3.1.4. PRICE-H and TruePlanner by PRICE® Systems Solutions

The PRICE-H cost estimation model was founded by Frank Freiman with its origins in military space applications. Based on his studies of statistical quality control, in 1969 he invented parametric cost modelling for hardware systems development and acquisition [98,101]. The PRICE-H Model was then established commercially by Mark H. Burmeister at the former RCA-Astro organisation, now Lockheed Martin, in Moorestown, New Jersey in 1975 [98]. Being developed to assist with bidding on payloads for military systems to DoD on intelligence satellites, the PRICE Systems Solutions now constitutes a market leading software distributed by Parametric Review of Information for Costing and Evaluation (PRICE) Systems internationally. A subscription for the software is required.

The PRICE Systems Solutions package is based on the parametric CEM, and consists of two sets of models, being the legacy PRICE Estimating Suite (PRICE-H and PRICE-S) and the new generation TruePlanner (True-H and True-S) [57]. Both PRICE models contain hundreds of CERs derived from extensive research and statistical analysis of data from over eleven thousand completed projects with defined product characteristics and known schedules, with most of the data points themselves sanitised and the database confidential. The PRICE Estimating Suite is not a dedicated space systems or launcher model, so applications extend across multi-disciplinary estimates. The model is however frequently applied to the space sector for hardware, software and scheduling estimations and project planning, particularly at the product concept stages [58]. Clients of the PRICE products include organisations like the DLR and NASA, which hold agency wide licenses on the software [55].

Since this paper has a hardware focus, only hardware models will be mentioned herein. To complement PRICE-H, the PRICE suite also includes the PRICE-HL (Hardware Lifecycle) and PRICE-M (Electronic Module and Microcircuit) models. PRICE-H has the capability to estimate most manufactured items and assemblies, and requires relatively detailed key inputs such as weight, manufacturing complexity, quantities, schedule information, development costs, and production costs [88]. The model must first be calibrated for each individual project by the user, which consequently allows for extraction of benchmark data for future implementation and reuse. This calibration is achieved through application of multiplication factors including the main Platform and Complexity parameters, the latter deemed to be the core of the PRICE hardware cost model being the universal metric for normalised cost density in a hardware item. A basic Platform Value allows for conversion of historical data to more modern applications by transcending different disciplines, and effectively considers different operational environments in terms of commercial, military ground, airborne, manned, and unmanned space. Complexity factors must be calibrated respective of product family, with the Engineering Complexity Factor addressing design standard and team experience in combination with a Manufacturing Complexity Factor. While the model facilitates for manual entry of parameter values, default Complexity values are also available.

The complementary PRICE-HL model generates operations and support cost outputs across all phases of a hardware life cycle. Additionally, the PRICE-M estimates electronic module and application specific integrated circuits (ASICs) development and production costs.

Most recently the new generation TruePlanner has replaced the functionalities of the modular PRICE-models. The new TruePlanner Suite, originally released in 2004, features advanced capabilities such as a Systems of Systems (SoS) framework [64], where all cost elements including hardware, software, IT, infrastructure and services, are combined within one single product breakdown structure (PBS). An optional capability for users to access and edit all underlying CERs means they can be modified readily. Alternatively data can be gathered, normalised and used as input for compiling user-specific CERs.

TruePlanner cost sensitivity can be quickly determined with inputs easily iterated and results varying to factor in changing assumptions. Consequently a cost value reflective of an acceptable level of risk can be determined and the range of cost uncertainty can be quantified and minimised [58].

3.1.5. aces by 4cost

The Advanced Cost Estimating System, *aces*, is a parametrics-based module of the 4cost suite, constituting cost estimating software for gauging plausibility of projects during the early stages. Released by the German company 4cost, this 'most innovative parametric model available' [102] was developed by a group of software, hardware and cost engineers and has been on the market since 1992. An annual license fee depending on the license type is relevant.

The *aces* model is a general all-purpose model applicable to compile cost estimates for mechanical and electronic hardware assemblies and systems as well as software programs [103], although calibration of the tool is necessary in line with respective historical company data. A built-in model for life cycle costs (LCC) allows *aces* to derive costs from acquisition stages, to preliminary design and development through to production and LCC analysis. Optional user calibration allows the model to function like a specific tool. Within the space industry *aces* has been used by companies and research institutions including OHB, MT Aerospace, DLR, and EADS Astrium.

The model is differentiated by the fact that it does not have an underlying database of past missions. Instead mathematical functions and algorithms (CERs) based on multi-disciplinary data collected and analysed over many years, form the basis of all cost estimates. As a deviation from the traditional processes, inputs like material lists and labour hours are therefore not needed. Instead, inputs pertain to economic conditions, manufacturing processes and development strategies [102], based on which only relevant inputs associated with an appropriate mode are highlighted for the user. Programmed using Visual Studio and C++, *aces* facilitates for common import and export interfaces in various formats including, amongst others, Excel© as well as text files [104].

The resulting output estimate provides an initial 'feasibility check' for a preliminary design, and cost information for hardware development, production and LCC trends. The output also reflects costs including those associated with design engineering, drafting, project management, documentation, system engineering, special tooling and test equipment, material, labour and any overheads. The model also provides estimates for subsystem integration and assembly costs and system testing [102].

3.1.6. SEER®-H by Galorath incorporated

Part of a family of products from Galorath Incorporated, the Systems Evaluation and Estimation of Resources (SEER) for Hardware, Electronics, & Systems (SEER-H) is a hybrid decision-support tool based on parametric and analogous CEMs. Used to formulate estimates for the total cost of newly developed projects, the software supports accurate project estimation and planning by determining scheduling and costs of development, production, operations, support and maintenance of new mechanical, electronic, structural, and hydraulic systems.

Particularly useful and relevant during initial project phases, SEER-H provides an early estimate of effort and cost, staffing, time to market, reliability and risk associated with production and maintenance of a new project [105]. Key inputs include weight, volume, material composition [88] information on project scope, including processes and location, as well as project complexity, technologies, and performance expectations.

The simulation and modelling engine is "based on sophisticated sector-specific mathematical models derived from extensive project histories, behavioral models, and metrics" [105]. A two-stage method is employed, the first step being an analogous comparison between the project of interest and a detailed, continually updated and current database of cost, programmatic and technical information. The second stage uses CERs to compare results of the analogy phase, with application of specially derived industry and company specific factors and multipliers.

The SEER-H interface provides the user with existing project templates which can be tailored and honed, or calibrated, for each specific project. Default industry-specific complexity and multiplication factors are also built-in through a dedicated 'Knowledge Bases' function for comparable projects. This facilitates initial estimates to be achieved quickly with very limited information then gradually updated and refined as more information becomes available.

The resulting estimate is then selected to be at component, sub-system or SoS level. While estimates are based on each component's unique design characteristics [58], added costs associated with the integration of single components into a complex, comprehensive system are also addressed by the software. The SEER-H output includes a range of detailed charts, graphs and reports for quick summarising and presenting of results.

3.2. GOTS cost estimation models and sources

This section outlines three sources of GOTS cost estimation models and tools frequently used for space sector cost estimation, as shown in Fig. 8.

Here, the NASA GOTS definitions is applied [57], referring to GOTS products as those specifically developed for a government agency by the agency itself, or sometimes by an external entity, although from funding, specification and strict controls enforced by the agency. Two sources reviewed here, NAFCOM and NASA's Cost Estimation Website are available to industry, while for completeness sake, although classified and restricted to governmental use only, the DoD LVCM is also outlined.

3.2.1. NASA/Air Force Cost Model (NAFCOM)

The NASA managed, automated cost estimation model was established in 1989 [51] and developed by Science Applications International Corporation (SAIC) [106] for the Marshall Space Flight Centre and the Air Force Cost Analysis Agency through currently eight versions with increasing capabilities [50], the most recent being NAFCOM11. Previously NASCOM, NAFCOM is a dedicated software parametric tool used for the cost estimation of space hardware. Based on comprehensive historical data from completed Air Force and NASA space programs, the Excel©-based NAFCOM uses weight relations to predict development and production costs of new space programs [50], and is optimally applied during early development phases of a project at subsystem or component level. Two versions of the software are available, a restricted government version and a Contractor Releasable version.

The NAFCOM database consists of technical and programmatic data across component, subsystem and space system levels with approximately 122 reference projects sourced from the Resource Data Storage and Retrieval Library (REDSTAR). Specifically, these include 76 unmanned earth orbiting and 24 unmanned planetary and 8 manned spacecraft including 366 scientific instruments, as well as 11 launch vehicles and 3 rocket engines

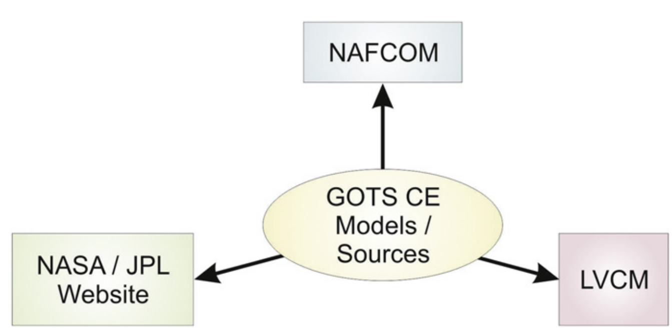

Fig. 8. Scope of reviewed GOTS cost estimation models and sources.

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[107]. Furthermore, the database of constituent missions is transparent, with resumes available for all projects used to derive CERs, with mission description, description of subsystem work breakdown structures (WBS), and any anomalies in the process outlined. NAFCOM has been widely used within the aerospace industry by not only civil contractors and organisations, but also by NASA HQ and Marshall Spaceflight Centre (MSFC) amongst others [107].

NAFCOM is predominantly a parametric model, and uses underlying multivariable CERs to obtain cost estimates across a broad scope of space hardware, including earth orbiting, manned and unmanned spacecraft, launch vehicles and upper stages, liquid rocket engines, and instruments. Of course within the scope of this review, NAFCOM applications for RLVs are of a niche focus.

To estimate costs, NAFCOM uses a WBS basis or alternatively a functional basis being work hours and dollars estimated for skillsets, materials and subcontracts [43]. Inputs allow the user to select historical data-points from the database to implement either a multivariable regression CER or a specific analogy approach to achieve their estimate. A tailored and specific user-defined approach is also possible [108]. Multiple cost driver inputs at subsystem level as well as complexity generators factoring in technical and programmatic complexities minimise input subjectivity and ensure that a data driven, statistically based estimate is achieved. Inputs for the NFACOM project include discrete technical parameters like weight, materials, power requirements and design life which can be extracted from program technical documentation. Inputs for other subjective cost drivers include contractor experience, management levels, technology level and any changes in requirements which are usually well documented in management reports and program reviews [43]. Process based schedule estimation also allows for three levels of schedules to be generated, while cost time phases show the cost spread at a subsystem level. In addition, cost trades facilitate for fast sensitivity analysis addressing weight, new design engineering or manufacturing management, and enhanced engine estimating functionality incorporating algorithms from the U.S. Airforce jet engine cost model [51]. Productivity gains are also incorporated through embedded time variables in most NAFCOM CERs, and through modelling of other engineering and manufacture technology improvements which reduce cost [107]. The output is then provided in two categories being Design, Development, Test and Evaluation (DDT&E) and production costs. Other calculated costs include IA&T, ground support equipment, system test operations, SE, launch and support operations, PM [108].

3.2.2. Aerospace Launch Vehicle Cost Model (LVCM) for DoD

The Department of Defense Aerospace Launch Vehicle Cost Model is a parametric model only available to the Aerospace Corporation project managers and cost analysts on an internal use basis [58]. Being governed by strict ITAR regulations, and with the incorporation of proprietary data from previous DoD launch vehicle programs, renders the LVCM as a classified tool for the commercial industry.

The fundamental purpose of the LVCM is to produce cost estimates of existing, modified and new launch vehicles by determining subsystem components of overall research, development, operations, testing and evaluation costs. Total vehicle LCC are also determined, and annual fiscal year funding for the overall vehicle program, established. In accordance with the parametric CEM, underlying CER equations relate cost as explicit functions of input variables [58].

Input variables must be entered by an experienced user who possesses a detailed knowledge of the input parameters, which include data about the foreseen launch site, propellant type, weight, and precedent production quantities of subsystems, amongst others including structure, thermal control, electrical power and wiring, reentry protection, landing system, C&DH, instrumentation, propulsion, payload fairing and more.

3.2.3. NASA Cost Estimation Website

This publicly available NASA/JPL website [69] features numerous educational examples through simple, on-line cost estimation models and tools encompassing a wide scope of purposes and frequently used for 'sanity checks'. All tools are written in JavaScript, and consequently require a browser with this capability.

Tools include inflation, learning curve and cost spreading calculators, with some launch vehicle data also provided. Specific cost estimation models then address aircraft and engines, software and mission operations, which include, amongst others, the DSN Cost Estimating Cost Model (CECM), the Mission and Space Operations Cost Models (MOCM and SOCM) and the Constructive Cost Model (COCOMO) Software Model. Only those models relevant to the space hardware of launch systems will be discussed further here. These are the Spacecraft/Vehicle Level Cost Model (SVLCM) and the Advanced Missions Cost Model (AMCM).

The SVLCM is a top level model which provides ROM cost estimates for spacecraft development and production, specifically including launch vehicle stages, engines and scientific instruments. SVLCM uses a common database with NAFCOM and is a simplified derivation thereof. User inputs include the type of spacecraft, dry weight, quantity and a learning curve factor if more than a single unit will be produced.

The AMCM offers another means to achieve fast ROM estimates for development and production costs of a wide scope of space, military and navy applications, including spacecraft and space transportation systems, aircraft, missiles, land vehicles, and ships. The AMCM is most suitable for use during early conceptual stages of a mission where few details are known at subsystem and system level and where multiple elements per scenario are foreseen. Input data includes unit production quantity (including spares, test and prototype units), mission type and dry weight, Initial Operating Capability (IOC) year (for spacecraft, this is the year of first launch), block number representative of the level of system design inheritance, and a complexity factor which encompasses the level of programmatic and technical difficulty analogously anticipated for the new system.

In addition to the cost estimation models and tools, the NASA Cost Estimation Website also offers a comprehensive scope of links to associations, organisations and agencies, as well as books, government and technical reports, periodicals, software and other references pertaining to cost estimation within the aerospace industry, making it in itself a valuable resource [69].

3.3. Cost estimation handbooks, reports and guides

This section outlines five prominent cost estimation handbooks, reports and guides specifically relevant and frequently applied within the space sector. These are the NASA Cost Estimating Handbook [55–57], the ISPA Parametric Estimating Handbook [89], the DoD Parametric Cost Estimation Handbook [58], the RAND Project AIR FORCE Reports [46–48], and the GAO Cost Estimating Assessment Guides [62,66,77] (Fig. 9).

Indeed numerous other resources and excellent handbooks and reports addressing cost estimation exist, such as the SSCAG Space Systems Cost Risk Handbook [57], or the FAA Life Cycle Cost Estimating Handbook [88] amongst others. These handbooks are numerous and generally tend to focus one particular elements of

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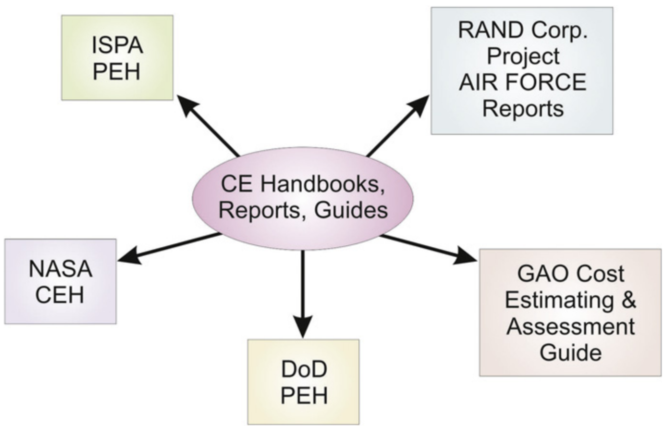

Fig. 9. Scope of reviewed cost estimation handbooks, reports and guides.

cost, such as cost risk or life cycle. Furthermore it is unreasonable to include every single handbook which, to varying degrees, may thematically pertain to cost estimation, and therefore the latter members are deemed beyond the scope of this paper.

3.3.1. NASA Cost Estimating Handbook

The NASA Cost Estimating Handbook (CEH) provides a very informative, concise overview on internal cost estimation within the National Aeronautics and Space Administration. NASA cost requirements as well as roles and responsibilities within the NASA framework are outlined, and cost estimation processes listed and explained. Four CEMs are stated, namely parametric, engineering build-up, analogy and ROM, with respective strengths and weaknesses stipulated. COTS and GOTS tools implemented within the NASA framework are also listed and functionally outlined, conveniently but not comprehensively. Dedicated chapters then address various aspects including financial analysis techniques, benefits assessment and analysis, cost risk, and career development.

The handbook itself is a living document and has undergone several iterations and modifications. The latest versions available include the NASA CEH 2002 [55], 2004 [56] and the most recent NASA CEH 2008 [57]. The handbook in itself is not an actual cost model, but rather a very informative and thorough piece of literature detailing cost estimation practice and processes employed and applied within NASA.

3.3.2. ISPA Parametric Estimating Handbook

The ISPA handbook is a joint compilation and publication from the International Society of Parametric Analysts, ISPA [78] and the Society of Cost Estimating and Analysis, SCEA [79]. The focus of the latest 4th edition of the living document is to provide a comprehensive guide to parametric practices and implementation for stakeholders, organisations and professionals in both industry and government [89]. Again, in itself, it is not a model, but rather a guide to consistent parametric practice.

The handbook explains the origins, validation and acceptability of parametric cost estimation, outlines the underlying theory and basis for CER development and implementation, describes the importance and means of data collection and analyses, and offers techniques and tools to improve cost estimation practice. In particular, applications of parametrics for proposal preparation, evaluation and negotiation are discussed. Various case studies are integrated within the document and general uniform guidance and best practices for cost estimation detailed and promoted.

3.3.3. RAND® Corporation Reports for Project AIR FORCE

Several documents addressing cost estimation practices have been produced by the nonprofit Research and Development Corporation RAND within the scope of Project AIR FORCE (PAF), a specially formed division of the RAND Corporation created by and for the United States Air Force. This federally funded research and development centre performs studies and analyses to address specific identified challenges and issues within industry.

In 1977 a RAND report critically assessed the validity of the parametric CEM for spacecraft current at the time, with a focus of improving estimates of future programs [46]. More recently in 2009, RAND released a stringently peer-reviewed technical report and handbook entitled “Guidelines and Metrics for Assessing Space System Cost Estimates” [48], based on a preliminary 2007 draft document [47]. The aim of this final handbook was to assist analysts with assessing cost estimates for space systems acquisitions, in particular for use by the DoD in response to an increased priority of space systems for US defense and security. Ultimately the handbook provides a comprehensive background on the challenges of cost assessment for space systems and offers information to facilitate for the evaluation of completeness, reasonableness, and consistency of space system cost estimates [48]. Chapters cover the basics of space systems within a DoD context, provide examples of average costs for past components, subsystems and systems from various space programs, and list some applicable cost models and their features, namely USCM, NAFCOM, and SSCM.

Another report from RAND Project AIR FORCE entitled “Improving the Cost Estimation of Space Systems. Past Lessons and Future Recommendations” [47], offers an instructive compilation of data, methods and information applicable to cost estimation, and through drawing upon past experience, makes suggestions for improving the processes, methods, tools and resources based on the study’s findings.

3.3.4. DoD Parametric Cost Estimating Handbook

This Parametric CEH [19] from the Department of Defense was established in 1994 as an initiative to study ways to expand the use of parametrics. Sponsored by a joint industry and Government Parametric Estimating Initiative (PEI) Executive Steering Committee and Working Group, the key goals were identified as providing training and background information in the areas of parametric use, evaluation and tools. The aim was to produce better cost estimates and ultimately reduce cycle times and lower costs [109].

The DoD Parametric Cost Estimating Handbook (PCEH) handbook defines the parametric CEM and addresses the topics of CER development, associated data collection approaches and data processing techniques. Examples of some specific existing parametric cost models for both hardware and software applied within industry are also provided and discussed. The DoD PCEH is freely accessible on the Internet [58], but has been assigned an ‘inactive model status’ by NASA signifying that although based on actual historical information, the data has not been recently updated [57].

3.3.5. GAO Cost Estimating and Assessment Guide

The United States Government Accountability Office (GAO) is entrusted with assisting the Congress in overseeing the federal government. In 2004 GAO released a document discussing the lack of disciplined cost estimating processes hindering the effective program management of NASA [77], highlighting the need for more formalised and standardised processes. Consequently in 2009, GAO released a document addressing cost estimation best practices and methods. While being a general, industry non-specific document, it provides a strict set of guidelines applicable within the space sector.

The "GAO Cost Estimating and Assessment Guide" [62] describes best practices and methodologies used by federal cost estimating organisations and industry to develop and manage capital program costs. The essential nature of generating credible, reliable cost estimates is emphasised in order to prevent occurrences of cost overruns, missed deadlines and performance shortfalls, whilst ensuring that reliable cost estimates are applied throughout the life of government acquisition programs. Through its 20 chapters and supporting appendices, the guide discusses other program LCC issues including cost estimate scope, scheduling, methods, validation, documentation, presentation and team, data acquisition, effective risk and uncertainty management, sensitivity analysis and respective best practices. Relevant and diverse case studies from previous GAO program reviews covering a wide scope of industries are integrated throughout the document to illustrate potential, typical pitfalls encountered in cost estimation.

3.4. An amalgamation approach to cost estimation

In order to obtain an overall system level cost estimate for a program, the mission elements must be costed with respect to their development, production and operations phases including launch and ground operations and support. The CEMs and range of available models, tools and resources reviewed within this paper are more suitable, in varying degrees, for use in particular circumstances and for specific applications during different project phases. It is therefore common for estimators to combine multiple different CEMs and also tools to obtain a hybrid cost estimate for an overall system. This approach can maximally support the various associated engineering tasks involved for large projects, while allowing for the comparison of cost models [4]. For example, in their paper which compares ESA and NASA cost estimation approaches and end results for a human mission to Mars, Hunt and van Pelt [110] list the various CEMs, being parametric CERs, PRICE-H, SEER-H, historical analogies and vendor quotes as the chosen methodologies to arrive at a preliminary estimate.

Here, two important points must be emphasised. The first being a distinction between a cost estimation methodology (CEM) and a cost estimation tool or model. CEMs refer to an underlying approach or principle of performing a cost estimate, like the parametric or analogy approaches. In turn, tools like PRICE-H [98] or *aces* [102,104], or the various available models like NAFCOM [49–51] and TransCost [87], refer to commercial, government or other products which are based around a specific underlying CEM. It is important to again stress that while a suitable method, model or tool is key for an estimation, the science of cost estimation also incorporates the essential elements of reliable data, as well as an experienced, knowledgeable estimator. Together, the three elements combine to produce a robust, justifiable estimate to support a realistic project budget.

Many of the significant cost estimations, in particular for large scale, complex, international projects like those undertaken within the space sector, rely on strategic combinations and amalgamations of numerous methods [88], and sometimes also numerous models and tools. Such a CEM and model amalgamation approach (AA) is utilised for two different yet complementary purposes. The first is to formulate an entirely new cost estimate which deals with the unique requirements and specification for a particular project, and where different CEMs better address the various project elements, components or processes to be costed. An example of this is where a system model, such as the SSCM, is applied, but where the resulting cost estimate is expressed as a sum of constituent sub-system cost estimates. The SSCM is a parametric-based tool. Here, the estimator may opt to take out particular sub-system estimate components and replace them with, for example an analogy or bottom-up estimate if more in-depth details are available for that sub-system, or if past experience can offer a more representative cost for that segment.

Alternatively AA can be implemented as a sanity check to an already existing estimate. This is often the case when a previously applied method has specific limitations known by the estimator, which undermines credibility of the resulting cost estimate. In such a case, AA may act as a staunch sanity check for the order of magnitude of the original estimate, to either support it, or put it into question. If the difference is significant, this may potentially indicate that an alternative CEM or tool should be applied, or that the original estimate should be reconsidered if the two are drastically divergent. True, it is important to be aware that the divergence could lie in the sanity check method itself, in which case the responsibility to make this critical distinction remains to be made by the estimator based on their expertise and experience.

Since numerous CEMs exist, many combinations of different methodologies are possible. Decision of which particular methods to combine and apply, is delegated predominantly by the project manager in close coordination with the cost estimator themselves. Open and consistent communication between the two parties at this stage is crucial, as is, of course, the experience and knowledge of the estimator. [53]. Such a decision integrates a number of determining factors which include the available information with respect to program definition and scope, specifications and requirements, expected level of cost estimate detail, and availability of resources such as costing tools or models, available data, finances, personnel and time. In any case, it is essential that any decision must be fully justifiable and defensible in scope of the latter constraints and overall project margins. In addition, close attention must be paid that each method or tool is implemented by a professional and experienced estimator who intricately understands the capabilities of their method or tool. After all, using a multitude of models does not automatically translate into a more accurate estimate if the methods are wielded by an inexperienced operator.

4. Discussion and conclusion

This paper aims to present a thorough and comprehensive review of key existing cost estimation methods as well as models, resources and tools relevant, and prominently applied within the space sector. Focusing in particular on hardware cost estimation, the time frame of interest for cost estimation is specified as being in the very early program phase, during the ongoing research, development and establishment of program requirements and specifications. Here, an indicative cost figure for successful program advancement is required, while only limited program information at system and subsystem level is available. The parametric approach is highlighted as being the most frequently utilised CEM within current tools for essential early phase mission costing. Parametric cost estimation also appears to underpin those readily accessible models identified to facilitate formulation of cost estimates for RLVs, including the TransCost and NAFCOM models, and the USCM8. While existing COTS tools, like those offered by PRICE, 4cost and SEER, are capable of producing interdisciplinary cost estimates based on user-defined complexity factors, these tools are characteristically too complex for application at a very early pre-Phase 0 since they fundamentally rely on a fairly detailed multitude of inputs and data. This data may still be in the analysis or design stage, and would therefore be either inconclusive and prone to change, or simply unavailable. Many of the commercial tools also feature confidential and closed databases at their core, and incur associated licence fees.

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Nevertheless they are included and described within this review due to their frequency of use, and for completeness.

Incomplete system requirements and mission specifications, coupled with limited project resources during very early pre-Phase 0 of a program due to a restricted research budget, mean that it is necessary to establish an alternative approach for such cases. This approach needs to be accessible, transparent yet justifiable and representative of program cost given the limited level of detail and information available at an early program stage. A simple, purely parametric-based approach is unlikely to yield an accurate estimate due to a distinct lack of precedence for launch vehicles, whether manned or reusable, therefore having an insufficient amount of historical data for effective CER formulation. Consequently new methods and approaches need to be further investigated, developed tested and validated, since parametrics and the analogy cost estimation approaches are effectively limited by their definition and input requirements of historical data. It is therefore foreseen that the analogy and EJ CEMs will be required in part, while AA may be adopted to facilitate for this future work. In this respect, approaches such as AHP which provide a structured estimation framework with EJ at its core, would play an increasingly vital and prominent role in cost estimation processes of the future. However considerably more research is needed into this area to establish defined approaches and guidelines to integrate and compile these processes into formal estimation methodologies. Either way, with the rapid development and metamorphosis of cost estimating processes and practices, deviations in estimation approaches within different organisations are likely to become more pronounced. This trend is underpinned by increased program complexities and structuring, as well as a significant advancement in technologies and thus knowledge capitalisation, processing and analysis concurrent with more stringent budgets and an overall program cost minimising focus [2]. As such, the roles of the cost estimation and cost engineering organisations and societies listed in this paper, will become significantly more important for moderating and encouraging common practices and standards within an increasingly deviating, classified and progressively competitive environment.

A broad scope of key models, tools, handbooks and resources addressing cost estimation with a COTS and GOTS hardware, system level focus are identified and discussed. Their features and applications, as well as strengths and weaknesses are highlighted. Most cost estimation tools and models described within this paper are also applicable within a broader sense. Beyond simply the scope of spacecraft projects, in some instances they can be applied within various terrestrial industries, including architectural, mechanical, aviation, and automotive applications. Complementary key handbooks and references mentioned also reiterate and support many central principles, concepts and best practices for cost estimation. Ultimately, the aim of this research and review is to establish key methodologies, factors and cost driving parameters which would then constitute the building blocks for a new approach or strategy capable of addressing simple, indicative cost estimation for very early phases of manned, reusable launch vehicles of the future. This paper consequently aims at providing a launch-pad for pursuing the next research objective and task of developing such an approach or strategy. This is done through identification and concise review of established, existing techniques, models, tools and resources with a focus of their associated parameters, features and factors, in view of consequent progression and development of such an approach.

References

[1] Koelle DE. Cost engineering, the new paradigm for space launch vehicle design. Journal of Reducing Space Mission Cost 1998;1:73–86.

[2] Greves D, Schreiber B. Engineering costing techniques in ESA, Cost Analysis Division, ESTEC, Noordwijk, The Netherlands.

[3] Liebers A. An architecture for cost control, the use of cost information in order-related decisions, PhD thesis, University of Twente, Enschede, The Netherlands, 1998.

[4] ten Brinke E. Costing support and cost control in manufacturing—a cost estimation tool applied to the sheet metal domain. PhD thesis, PrintPartners Ipskamp, University of Twente, Enschede, The Netherlands, 2002.

[5] European Cooperation for Space Standardization. ECSS-M-ST-60C, Space project management—cost and schedule management. The Netherlands: ESA Requirements and Standards Division, ESTEC; 2008.

[6] Maryniak GE. When will we see a Golden Age of Spaceflight? Space Policy 2005;21:111–9.

[7] Innovative Strategies for Space Competitiveness: Assessing the SpaceIsle's Policy and Results, Futron Corporation, February 2011.

[8] SPACECAST2020, The World of 2020 and Alternative Futures, Air University Education and Training Command United States Air Force, Maxwell Airforce Base, Alabama, June 1994.

[9] Laing J, Crouch GI. Vacationing in space: tourism seeks 'New Skies'. In: Singh TV, editor. New horizons in tourism—strange experiences and stranger practices. Oxfordshire, UK: CABI Publishing; 2004. [chapter 2].

[10] Crouch GI, Devinney TM, Louviere JJ, Towhidul I. Modelling consumer choice behaviour in space tourism. Tourism Management 2009;30(3):441–54.

[11] Kothari A, Webber D. Potential demand for orbital space tourism opportunities made available via reusable rocket and hypersonic architectures. American Institute of Aeronautics and Astronautics (AIAA); 2008.

[12] Penn JP, Lindley CA. Requirements and approach for space tourism launch system. Acta Astronautica 2003;52:49–75.

[13] Suborbital Space Tourism Demand Revisited, Futron Corporation, August 2006.

[14] Crouch GI. Researching the space tourism market. Presented at the annual conference of the travel and tourism research association, June 2001.

[15] Collins P, Isozaki K. The Japanese Rocket Society's space tourism research. In: International symposium of space tourism, 20–22 March 1997, Bremen.

[16] Collins P, Iwasaki Y, Kanayama H, Ohnuki M. Commercial implications of market research on space tourism. Journal of Space Technology and Science 1994;10(2):3–11.

[17] Commercial Space Transportation Study, 1 April 1997 [Online]. Available: 〈http://www.hq.nasa.gov/webaccess/CommSpaceTrans/〉 [accessed 24 June 2011].

[18] O'Neil D, Bekey I, Mankins J, Rogers TF, Stallmer EW. General public space travel and tourism—volume 1 executive summary. National Aeronautics and Space Administration (NASA) and Space Transportation Association (STA); 1998.

[19] Collins P, Stockmans R, Maita M. Demand for space tourism in America and Japan, and its implications for future space activities. Advances in Astronautical Sciences 1995;91:601–10.

[20] Abitzsch S. Prospects of space tourism. In: 9th European aerospace congress—visions and limits of long-term aerospace developments, 15 May 1996, Berlin.

[21] Barrett O. An evaluation of the potential demand for space tourism within the United Kingdonm, Bournemouth University, Dorset, England, 1999 [Online]. Available: 〈http://www.spacefuture.com/〉 [accessed 17 December 2010].

[22] Crouch GI, Laing JH. Australian public interest in space tourism and a cross-cultural comparison. Journal of Tourism Studies 2002;15(2).

[23] Mealey A. Space Tourism Survey [Online]. Available: 〈http://www.spacetourismnow.com/blog/index.php/space-tourism/space-tourism-survey/〉 [accessed 8 June 2011, 8 August 2011].

[24] Virgin Galactic Official website [Online]. Available: 〈http://www.virgingalactic.com/〉 [accessed 29 June 2011].

[25] Batey A. Your flight is now departing from space terminal 1: the amazing story behind Branson's Virgin Galactic project, 5 June 2010 [Online]. Available: 〈http://www.dailymail.co.uk/〉 [accessed 15 November 2011].

[26] Floreani D, Wood L. Internet to orbit—exloring the potential of IP networking technologies in space. Packet Magazine 2005;17(3). CISCO Systems Inc..

[27] Hart K. Travel Agency launches tourists on out-of-this-world adventures. The Seattle Times Business and Technology, 2 April 2007 [Online]. Available: 〈http://seattletimes.nwsource.com/html/businesstechnology/〉 [accessed 21 March 2011].

[28] Space Adventures Official website [Online]. Available: 〈http://www.spaceadventures.com/〉 [accessed 24 March 2011].

[29] Armadillo Aerospace Official website [Online]. Available: 〈http://www.armadilloaerospace.com/〉 [accessed 21 March 2011].

[30] SpaceX Official website [Online]. Available: 〈http://www.spacex.com/〉 [accessed 21 February 2011].

[31] Eilingsfeld F. Estimating the development cost of an orbital passenger spaceplane. Ruesselsheim, Germany: Case study for the International Space University, PRICE Systems Deutschland; 2006.

[32] Sippel M. Promising roadmap alternatives for the SpaceLiner. Acta Astronautica 2010;66:11–2.

[33] van Foreest A, Sippel M, Klevanski J, Guelhan A, Esser B. Technical background and challenges of the spaceliner concept. In: 7th International Symposium on Launcher Technologies, Barcelona, Spain, 2007.

[34] van Foreest A, Sippel M. The logistical challenges of the SpaceLiner concept. In: Proceedings of IAA first symposium on private human access to space. Arcachon; May 28–30, 2008.

[35] Sippel M. SpaceLiner - a visionary concept of an ultra fast passenger transport under investigation in FAST20XX, AIAA 2009-7439. In:

Proceedings of 16th AIAA/DLR/DGLR international space planes and hypersonic systems and technologies conference. Bremen; 2009.
[36] Suborbital Price Drop Foreseen by 2014, Space News International, 23 July 2003.
[37] Remarks by the President of Space Exploration in the 21st Century, The White House, Office of the Press Secretary, John F. Kennedy Space Centre, Merritt Island, Florida, 2010.
[38] Klepper S. Industry life cycles. Industrial and Corporate Change 1997;6(1).
[39] Peeters W. From suborbital space tourism to commercial personal spaceflight. Acta Astronautica 2010;66:1623–5.
[40] Quester PG, McGuiggan RL, Perreault WD, McCarthy EJ. Marketing: creating and delivering value.4th ed. Australia: NSW: McGraw-Hill; 2004.
[41] Perrault WDJ, McArthy JE. Essentials of marketing, Chicago: Richard D. Irwin Company, 1997.
[42] Johnson RF, Smith PL. Future spacelift projections. Space Policy 1998;14:145–51.
[43] Hammond WE. Space transportation: a systems approach to analysis and design, AIAA education series. Virginia: American Institute of Aeronautics and Astronautics Inc.; 1999.
[44] Hendrickx B, Vis B. Energiya-Buran The Soviet Space Shuttle. Chechester, UK: Praxis Publishing Ltd.; 2007.
[45] Old Model Doesn't Apply to SpaceX's Expenditure (Letter), Space News International, 7 February 2011.
[46] Dryden JA, Large JP. A critique of Spacecraft Models, R-2196-1-AF, The RAND Corporation, Project AIR FORCE, 1977.
[47] Younossi O, et al. Improving the cost estimation of space systems—past lessons and future recommendations, 2008.
[48] Fox B, Brancato K, Alkire B. Guidelines and metrics for assessing space system cost estimates. The RAND Corporation, Project AIR FORCE; 2008.
[49] Unmanned Space Vehicle Cost Model, 8th ed., California, 2002.
[50] NASA/Air Force Cost Model NAFCOM, Science Applications International Corporation, May 15, 2002.
[51] Smith K. NASA/Air Force Cost Model NAFCOM. In: 2002 SCEA national conference, Science Applications International Corporation, June 2002.
[52] Small Satellite Cost Model website, Aerospace Corporation [Online]. Available: 〈http://www.aero.org/capabilities/sscm/index.html〉 [accessed 7 December 2010].
[53] Meisl CJ. Techniques for cost estimating in early program phases,. Engineering Costs and Production Economics 1988;14:95–106.
[54] Curran R, Raghunathan S, Price M. Review of aerospace engineering cost modeling: the genetic causal approach. Progress in Aerospace Sciences 2004;40:487–534.
[55] 2002 NASA Cost Estimating Handbook. National Aeronautics and Space Administration, Washington, DC, 2002.
[56] 2004 NASA Cost Estimating Handbook. National Aeronautics and Space Administration, Washington, DC, 2004.
[57] 2008 NASA Cost Estimating Handbook. National Aeronautics and Space Administration, Washington, DC, 2008.
[58] DoD Parametric Cost Estimating Handbook. Department of Defense and Parametric Estimating Initiative Steering Committee, September 1995 [Online]. Available: 〈http://cost.jsc.nasa.gov/pcehhtml/pceh.htm〉 1995. [accessed 13 September 2010].
[59] Roy R. Cost engineering: why, what and how? UK: Cranfield University; 2008. July.
[60] Humphreys K, Wellman P. In: Dekker M, editor. Basic cost engineering, New York: 3rd ed., revised and expanded, 1996.
[61] Roy R, Kelvesjo S, Forsberg S, Rush C. Quantative and Qualitative Cost Estimating for Engineering Design, Cranfield University, Cranfield, Bedford, UK [Online]. Available: 〈http://cranfield.academia.edu/RajkumarRoy/Papers〉 [accessed 26 January 2011].
[62] GAO-09-3SP, GAO Cost estimating and assessment guide; best practices for developing and managing capital program costs, United States General Accounting Office, March, 2009.
[63] Miller DW, Keesee J, Jilla C. Space systems cost modeling. MIT Aeronautics and Astronautics Course; 2003.
[64] Shermon D. Systems cost engineering—program affordability, Management and Cost Control. USA: Gower Publishing Limited; 2009.
[65] Arena MV, et al. Impossible certainty: cost risk analysis for air force systems. The RAND Corporation; 2006. Project AIR FORCE.
[66] Albert NF. GAO cost assessment guide: best practices for estimating and managing program costs. Virginia: MCR Proprietary; 2008.
[67] Hamid Habib-Agahi, Eric Kwan. NASA instrument cost model (NICM) presented to the NASA cost symposium; April, 2005.
[68] Boehm WB, Reifer JD, Valerdi R., COSYSMO: a systems engineering cost Model, University of Southern California, Centre for Software Engineering, California.
[69] NASA/Jet Propulsion Laboratories Cost Estimation Website [Online]. Available: 〈http://cost.jsc.nasa.gov/〉 [accessed 13 September 2010].
[70] Space Operations Cost Model, SOCM. Final Report for Option 2 Contract Year, SAIC, December 2007.
[71] Schishko R. Model for Estimating Space Station Operations Cost (MESSOC),. NASA/ JPL; 2004.
[72] Remer DS, Buchanan HR., A model for the cost of doing a cost estimate, The Telecommunications and Data Acquisition Progress report 42-110, p. 278–83, Jet Propulsion Laboratory, Pasadena, California, 15 August 1992.
[73] Make or Break: Why Accurate Cost Estimation is Key, ExecutiveBrief: Project Smart, 2008.
[74] Young JA, Markley T. A better cost estimating tool: the key to not going over budget. Defense AT&L, July–August 2008, p. 23–6.
[75] de Selding PB. ESA Determined To Learn from the Mistakes of BepiColombo, Space News international, 4 December 2009.
[76] de Selding PB. Europe's ATV Program Facing Launch Delay, Cost Overruns, Space News International, 20 October 2003.
[77] GAO-04-642, NASA, lack of disciplined cost-estimating processes hinders effective program management, United States General Accounting Office, May, 2004.
[78] International Society of Parametric Analysts website [Online]. Available: 〈http://www.ispa-cost.org/〉 [accessed 1 October 2010].
[79] Society of Cost Estimating and Analysis website [Online]. Available: 〈http://www.sceaonline.org/〉 [accessed 4 October 2010].
[80] Space Systems Cost Analysis Group website [Online]. Available: 〈https://sscag.saic.com/〉 [accessed 1 October 2010].
[81] Association for the Advancement of Cost Engineering through Total Cost Management International website [Online]. Available: 〈http://www.aacei.org/〉 [accessed 1 October 2010].
[82] American Society of Professional Estimators website [Online]. Available: 〈http://www.aspenational.org/〉 [accessed 1 October 2010].
[83] The Association of Cost Engineers website [Online]. Available: 〈http://www.acoste.org.uk/〉 [accessed 4 October 2010].
[84] International Cost Engineering Council website [Online]. Available: 〈http://www.icoste.org/〉 [accessed 5 October 2010].
[85] Hughes RT. Expert judgement as an estimating method. Information and Software Technology 1996;38:67–75.
[86] Federal Acquisition Regulation website [Online]. Available: 〈https://www.acquisition.gov/Far/〉 [accessed 22 October 2010].
[87] Koelle DE. Handbook of cost engineering for space transportation systems including TransCost 7.3, Revision3. Germany: TransCostSystems; 2009.
[88] Investment Cost Analysis Branch ASD-410, Life cycle cost estimating handbook: parametric, analogy, engineering estimation risk analysis modeling and simulation, Version 0.2, Federal Aviation Authority (FAA), June 2002.
[89] International society of parametric analysts and the society of cost estimating and analysis parametric estimating handbook, 4th ed., Vienna.
[90] Lillie CF, Thompson BE. Parametric cost estimation for space science missions. SPIE Paper 7018-81, June 2008.
[91] Meyer MM, Booker JM. Eliciting and analyzing expert judgement—a practical guide. American Statistical Association and the Society for Industrial and Applied Mathematics; 2001.
[92] Kitchenham B. Making process predictions, software metrics: a rigorous approach. New York: Chapman & Hall; 1991.
[93] Rush C, Roy R. Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cycle. In: Proceedings of the CE2000 conference, 17–21 July 2000, Lyon, France.
[94] Saaty TL. The analytic hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill; 1980.
[95] Haas R, Maixner O. An illustrated guide to the analytic hierarchy process presentation slides. Institute of Natural Resource and Applied Life Sciences, Vienna.
[96] Saaty TL. Decision making with the analytical hierarchy process,. International Journal of Services Sciences 2008;1(1):83–9.
[97] Kasperczyk N, Knickel K. The Analytic Hierarchy Process (AHP) [Online]. Available: 〈http://www.ivm.vu.nl/en/Images/MCA3_tcm53-161529.pdf〉 [accessed 28 June 2011].
[98] PRICE Systems website [Online]. Available: 〈http://pricesystems.com〉 [accessed 5 October 2010].
[99] U.S. Department of State Directorate of Defense Trade Controls, International Traffic in Arms Regulations [Online]. Available: 〈http://www.pmddtc.state.gov/regulations_laws/itar_official.htm〉 [accessed 9 February 2011].
[100] The Aerospace Corporation website [Online]. Available: 〈http://www.aero.org/〉 [accessed 22 July 2010].
[101] Apgar H. A tribute to Frank Freiman, ISPA Parametric World. A newsletter to the International Society of Parametric Estimators 2010;29(1).
[102] 4cost website [Online]. Available: 〈http://www.4cost.de/en/software/parametric-cost-estimating〉 [accessed 14 September 2010].
[103] General Overview of the aces Cost Estimation Model, Advanced Cost Estimating System, 4cost GmbH, Berlin, Germany.
[104] 4cost=Interactive and Integrated Management method for Software and Product Costing, 4cost GmbH, Berlin, Germany.
[105] SEER by Galorath Incorporated website [Online]. Available: 〈http://www.galorath.com/〉 [accessed 14 September 2010].
[106] Science Applications International Corporation website [Online]. Available: 〈http://www.saic.com/〉 [accessed 15 November 2010].
[107] NASA ESAS Final Report—ExplorationSystem Architecture Study, NASA, November, 2005.
[108] Leisman GA, Wallen AD. Design and analysis of on-orbit servicing architectures for the global positioning system constellation thesis, Air Force Institute of Technology, US, March 1999.
[109] Deutsch M. Parametric cost estimating, a joint industry/government initiative, expanding parametric cost estimating. Lockheed Martin Astronautics; September 1997.
[110] Hunt CD, van Pelt MO. Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars, NASA MSFC, Huntsville, USA and ESA-ESTEC, Noordwijk ZH, The Netherlands, 2004.

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