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# A Combined Technical and Economical System Model for LEO Satellite Constellations

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## Abstract

The paper presents a systematic modelling approach for complex technical systems operating in a commercial environment, such as LEO satellite constellations for mobile communication and multimedia services.

The proposed modelling approach allows to estimate in a systematic way the *complete life cycle costs*, i.e. development and operational costs (investment) and the *operational revenue* linked in a systematic to the functional properties of a commercial technical system. In this sense the model extends in a considerable way the conventional engineering cost models, which consider more or less only certain subsets of the life cycle costs.

The *technical model* consists of a *system requirements model* and a *functional reference model* (*Structured Analysis Method - SA*) of all elements involved (satellite(s), payload capabilities, ground station, mission control, operating personnel, launch) and allows to allocate in a systematic way parametric weights for the technical parameters. A mapping of these parameterised functional models into the *physical domain* (equipment, element) is based on appropriate reference data bases (e.g. previous projects) and allows the generation of specific metrics, e.g. mass/power/size budgets. The economic model is based on a *cost model* which maps the physical model using *Cost Estimating Relationships (CER)* . A complementary *market model*, which is based also on the technical parameters of the LEO constellation, completes together with a *capital value model* the overall *techno-economical system model*.

A PC-based prototype implementation of the system model has been performed in a *Microsoft Excel*™ environment. The preliminary validation shows a satisfactory correspondence with available public data for IRIDIUM and GLOBALSTAR and allows sensitivity studies for different scenarios.

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## 1. INTRODUCTION

### LEO Satellite Constellations

For commercial space systems with private investment, such as LEO satellite constellations for mobile communication and multimedia services, the key optimality criterion is the *return on invested capital.* This issue has to be considered carefully within the systems engineering process, because the optimality criterion is governed by economical goals rather than by pure technical goals. The complexity of LEO communication satellite constellations arise mainly from its globally distributed character (users/customers, satellites, ground stations), its mobility and direct user access properties. Recent experiences with the currently implemented commercial constellations *Iridium* and *Globalstar* show the strong link between the technical and economical properties (Iridium: malfunctioning of satellites, revenue delays; Globalstar: launch failures, delay of start of service).

### State of the Art Systems Engineering

*Systems engineering* is commonly understood as the design process of a technical system under consideration of various constraints [ESA96]. In this sense it is state of the art of modern systems engineering, to incorporate also economic constraints in the design considerations.

Conventional approaches incorporate *cost models* and allow appropriate system optimisation in the sense of the "design to cost" paradigm [LARS92], [BELL95], [PARK96], [SCHW9X], [MOIS95].

However such 'cost optimal' solutions (in general *minimum* cost) are not necessarily optimal in the more general economic sense.

The first deficit results from the different level of coverage of cost issues. It is quite evident that cost in terms of invested money must cover the total investment in terms of *life cycle costs*, i.e. the cumulated investment for development, operations and even de-installation. Many engineering approaches are dealing only with the development costs.

The second deficit results from the fact, that the ultimate goal of the system *"to earn money by providing appropriate services on a market"* is not covered at all or only in a weak manner in many systems engineering processes. The reason for this deficit seems to be the very different natures of technical and economics domains, which makes it difficult to establish and to handle appropriate integrated conceptual models.

### Techno-Economic System Modelling

To guarantee a proper system design with a complete economic view it is therefore necessary, to establish more complete techno-economical models which provide in a systematic and transparent way a traceability between technical and economic properties up to market and end-user level.

Only on the basis of such models it is possible to perform sound trade-off analyses for different design variants and to implement appropriate design corrections according to specific optimisation criteria.

This paper presents such a *combined* technical and economic model. The application of the system model is shown to answer a design question in the area of *automation & control* : *'what is the best strategy of implementing automation: high onboard autonomy or ground automation ?'*. It is shown, that pure optimisation at cost level (even *life cycle costs*) would lead to different and probably worse solutions than an overall economic optimisation.

## SYSTEM MODELLING APPROACH

A typical *system design process* can be briefly summarised as follows:

The design team starts with a certain set of *system requirements,* constructs some *candidates* for *design variants* and has to *select* on the basis of relevant *measurable properties* (metrics) what design variant meets *closest* the original system requirements.

The difficulties in this process arise due to following facts:

- establishment of design variants is an ambiguous process with many degrees of freedom (*e.g. 'you can implement a required radio data link with various modulation techniques'*)
- technical and economic properties of a technical system are mutually linked (e.g. *'a 1000 channel data link needs less power, less volume etc. but provides also less service and revenue capabilities on the market'*).
- The metrics to measure these properties must link technical and economic domains, i.e. they must be compatible.

The joint *techno-economic system model* which is presented in the subsequent paragraphs tries to overcome these difficulties by the establishment of a engineering reference design strategy, defining in a clear and unambiguous way appropriate *measurable properties* and their *mutual relationship*.

### Modelling Method

An appropriate techno-economic model has to describe the following abstract properties of a technical system at different levels:

- different views of the system, called *domains* (e.g. functional, physical, cost)
- domain specific *properties* (e.g. functions, performances, cost items)
- *relations* between the properties of different domains.

For this purpose a *set theoretic notation* has been chosen with the following conventions (Figure 1):

$\Sigma_J$, $\Sigma_K$ ... sets of properties in domain J and K

$\varepsilon_{J,i}$ , $\varepsilon_{K,j}$ ...elements of sets J and K

$\Re_{J/K}$ ... relation (function) mapping set J to set K (the arrow denotes only the primary direction of mapping, it does not say if the relation is *injective, surjective or bijective*.)

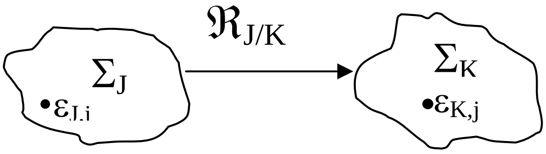


Fig.1: Modelling elements

This modelling approach supports in a straightforward way the implementation of the model in a relational data base system, i.e. the elements of the sets **Σ** represent the individual data items and the relations **ℜ** represent the relational mapping between these data items.

In this sense we use the following *model definition* throughout this paper:
A *system model* for *domain K* consists of its *set of properties* $\Sigma_K$ and *all relations* $\Re_{i/K}$ which link domain K to other domains **i**:

**model_K** := $\{ \Sigma_K, \Re_{i/K} \}$, i=1,... no. linked domains

## Techno-Economic System Model

The structure of the joint *techno-economic system model* is sketched in Figure 2. It consists of the following *domains* (i.e. views on the system):

$\Sigma_R$ ... *System Requirements Domain*
⇒ specification how the system should behave from the user/customer point of view

$\Sigma_F$ ... *Functional Domain*
⇒ specification of technical functions and performances

$\Sigma_P$ ... *Physical Domain*
⇒ budgets (e.g. performances, mass, power) based on a concrete realisation with physical elements (equipment)

$\Sigma_C$ ... *Cost Domain*
⇒ all life cycle cost elements for a concrete physical realisation

$\Sigma_{EE}$ ... *Economic Environment Domain*
⇒ financial, political, social constraints

$\Sigma_M$ ... *Market Domain*
⇒ products & services for end-users for a specific design variant

$\Sigma_V$ ... *Capital Value Domain*
⇒ current value of all profits for a specific design variant

During the system design process it is necessary, to determine concrete elements $\varepsilon$ of the different sets (domains).

There are two distinguished domains, which do *not* have direct functional *dependencies* from

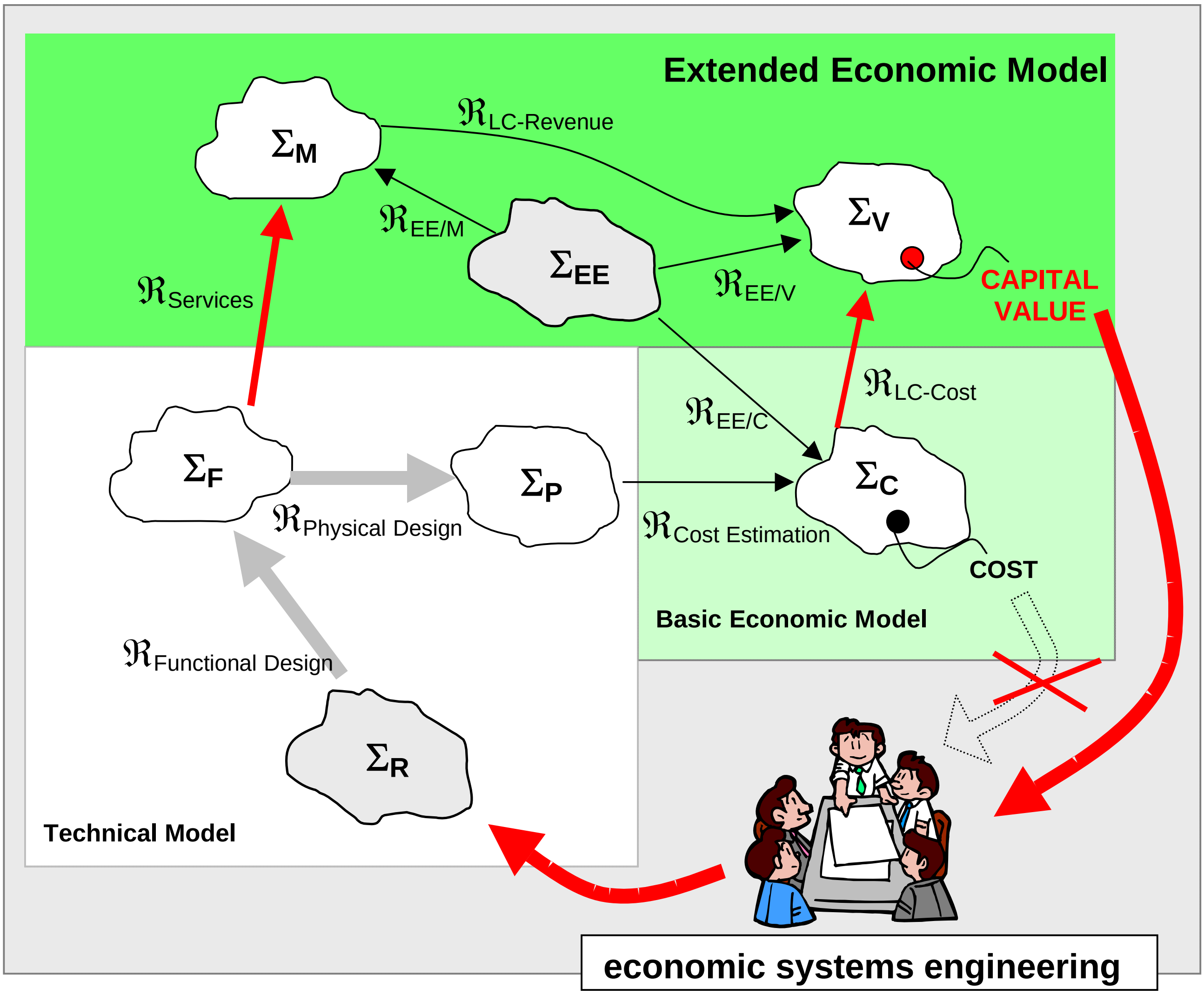


Fig.2: Techno-Economic System Model

others, namely the *system requirements* domain $\Sigma_R$ and the *economic environment* domain $\Sigma_{EE}$. This means from the system design point of view, that the elements $\varepsilon$ of these domains must be specified *a-priori* on the basis of *expert knowledge*, i.e. they are free parameters for the design problem (→ increases the degrees of freedom for design choices by the design team).

In contrary the elements of all other domains result as more ore less *causal consequences* in terms of a relational mapping from one domain into the other. This intellectual engineering task is modelled in the system model by *relations* $\Re$ (functional mapping).

Looking at these relations, it can be seen that two of them, $\Re_{\mathbf{Functional\_Design}}$ , $\Re_{\mathbf{Physical\_Design}}$ are *completely* subject to *intellectual design decisions* of the design team and cannot be formalised (in the best case decision support by an expert system is possible, but this option will not be treated in the current paper).

The other relations $\Re_{\mathbf{Cost\_Estimation}}$ , $\Re_{\mathbf{Services}}$, $\Re_{\mathbf{Environment}}$ , $\Re_{\mathbf{Life\_Cycle\_Revenue}}$ and $\Re_{\mathbf{Life\_Cycle\ Cost}}$ can be received in a more formal way through application of *analytical relations* (formulas etc.).

Moreover the *first group* of relations are *non bijective relations*. For example a *single* requirement can be detailed by *several* functions ($\rightarrow\Re_{\mathbf{Functional\_Design}}$), so it is not possible unambiguously to conclude backwards from an existing function what was the originating requirement. This is the reason, why an analytical solution to the overall system optimisation problem is not feasible at all.

For the *second group* of relations it is much easier to find *formal, analytical relations* (e.g. Cost Estimating Relationships, market rules).

The benefit of such a formalised system model lies in its ability that it can be easily implemented in a *computer based tool*. It is obvious from the model topology that it is *mandatory* to implement the *Functional Model* $\Sigma_F$ in a *strictly formal* way, because it serves as baseline also for the economic models.

A formal implementation of the System Requirements Model $\Sigma_R$ is desirable for traceability purposes, but it is not mandatory (it has no direct links to the economic models because its information contents are to fuzzy with respect to the actual realisation).

### Prototype Computer Implementation

A PC-based prototype implementation of the system model has been performed in a *Microsoft Excel*™ environment [PFOR98].

## TECHNICAL MODEL

### System Requirements Model

The *System Requirements Model* $\{\Sigma_R\}$ contains all requirements stated by the user/customer of the system in the usual way (functional, performance, handling, general constraints).

These requirements build the design basis for all subsequent design steps. Modern system engineering approaches require a careful maintenance of the requirements. Therefore it is todays common practice to use formal and computer-aided specification methods already at the requirements level, e.g. *Structured Analysis (SA)* [YOURD89].

### Functional Model

The *Functional Model* $\{\Sigma_F , \Re_{\mathbf{Functional\_Design}} \}$

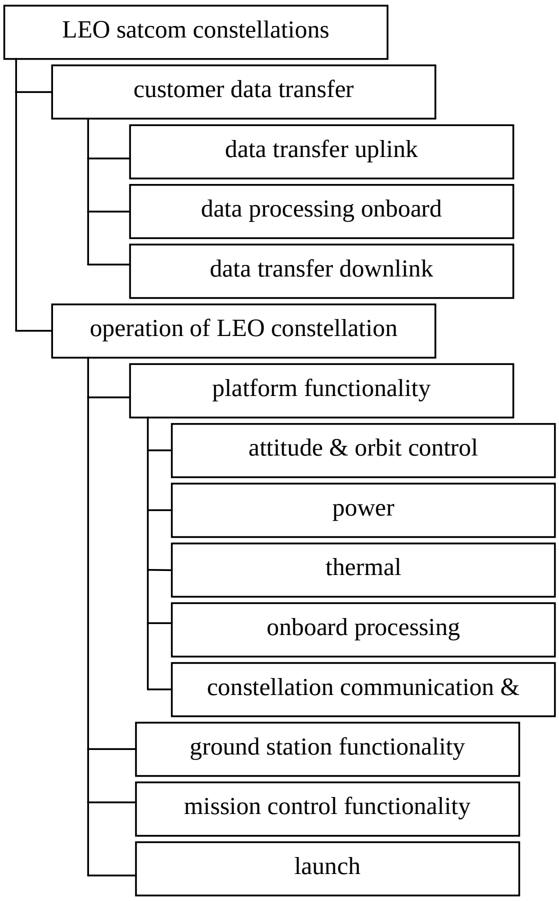


Fig.3: Hierarchy of the Functional Model for a LEO Satellite Constellation

is the *core* of the system model, because it defines completely the technical properties and it serves as main source for the economic model.

For the current system class *'LEO satellite constellations'* a generic functional model has been established using the Structured Analysis (SA) method [YOURD89]. It models all required functions including the space segment, ground segment, launch and communication services. The *top level hierarchy tree* of the Functional Model is shown in Figure 3.

At this design level the most important design decisions are taken and those decisions govern the technical as well as the economic performance. A good example is the basic design question how to implement *properly system redundancy* for a LEO constellation: (a) high onboard redundancy of any single satellite *versus* (b) redundancy at satellite level (spare satellites). The selected concept governs completely the final physical architecture of the system and consequently the economic properties.

### Physical Model

The *Physical Model* $\{\Sigma_P , \mathfrak{R}_{Physical\_Design} \}$ can be established by selecting concrete physical elements to realise the functions as specified by the Functional Model $\Sigma_F$. The mapping process modelled by $\mathfrak{R}_{Physical\_Design}$ is also an intellectual decision process, but it may be supported in an efficient way by expert knowledge resulting from past projects. This means that on the basis of physical data bases (equipment, components, etc.) it is possible at least to calculate in some automatised way the relevant physical properties (budgets) in a straightforward manner.

## ECONOMIC MODEL

The economic model can be split into two submodels (Figure 3):

- Basic Economic Model
- Extended Economic Model.

Conventional systems engineering approaches work with the Basic Economic Model only, which uses cost properties, which can be derived from the Physical Model $\Sigma_P$. But to compare realistic different alternatives of realisations under comprehensive economic aspects it is necessary to include the return on invested money by using the *capital value* (in particular the value of the current profit). The costs were calculated by using the comprehensive *life cycle costs analysis*, because of the very high share of operations costs in such long-term investment projects like LEO satellite constellations (Figure 5). The overall economic model consists therefore of four submodels: the *cost model*, the *economic environment model*, the *market model* and the *capital value model*.

### Cost Model

The *Cost Model* $\{\Sigma_C , \mathfrak{R}_{EE/C}, \mathfrak{R}_{Cost\_Estimation} \}$ determines the costs of the system during its whole life cycle (from concept studies to the disposal of the components). The system costs of long-term investment projects can be determined by using one of the following five methods [GREV95]:

- Bottom-up method
- Analogies
- cost estimating functions

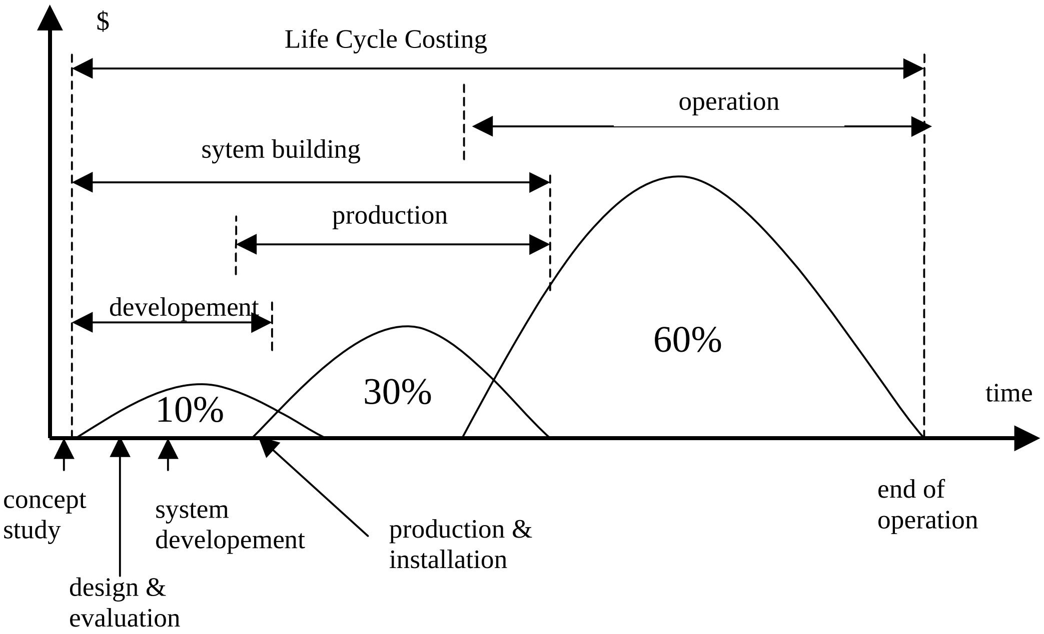


Fig.5: Typical *Life Cycle Costs Model* for a space project [LARS92]

- parametric cost estimating relationships (CER)
- Using expert knowledge

The bottom-up method provides the most exact cost forecasts. Unfortunately the underlying technical levels are not available in early project phases. That is why it is more convenient to use another, also exactly cost forecast method, the parametric *cost estimating relationships* (CER). CER is in use in many other areas, for instance in building projects, aircraft construction and very often in space projects. A CER has the following mathematical form:

$$c = f\left(p_1, p_2, \dots\right)$$

c...costs; $p_i$...parameter i

The CER´s can be generated by using the statistical regression analysis to historical data of former competitive (space-) projects [NASA98]. The cost model used for the current investigations is based on the CER´s given in [LARS92]. Figure 6 shows the main input parameter for the CER model.

To forecast the comprehensive life cycle costs the authors had to find mathematical functions to calculate the costs of operation and disposal of LEO satellite constellations.

The costs of production consider economic learning effects (static and dynamic economies of scale). Furthermore reliability studies (using redundant components, replacing unreliable space or earth segments) and the ongoing technologic development have been taken into account.

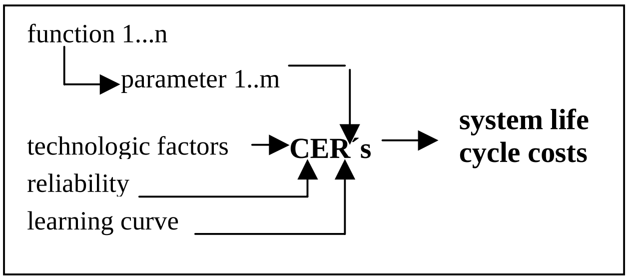


Fig. 6: The input parameters of the CER's

Cost critical items are the estimation of efforts for software (lines of code), space and ground segment and launch. The structure of the cost model is given in Figure 7.

The costs were calculated for a defined period (for instance a year).

The preliminary validation results of the cost model are comparable to estimations given in relevant publications (± 5%). In future studies it could be interesting to generate new CER´s by using now available data of meanwhile existing LEO satellite constellations like Iridium, Globalstar or ICO.

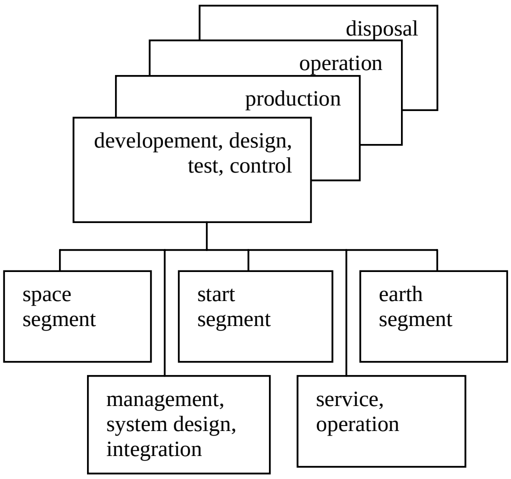


Fig. 7: The structure of the life cycle model

**Economic Environment Model**

The *Economic Environment Model* $\{\Sigma_{EE}\}$ substantiates the general assumptions about relevant economic parameters. In particular the following relations to other domains are modelled (see Figure 2):

$\mathfrak{R}_{EE/C}$:
- expectations about inflation
- trend of prices
- trade barriers in the field of high-technology
- cost of capital

$\mathfrak{R}_{EE/M}$:
- trends of prices (alternative or competing systems)
- roaming contracts with companies around the world
- expectations about inflation
- barriers to regional markets
- forecast of the demand

$\mathfrak{R}_{EE/V}$:
- influences on the interest rate
- duration of the life cycle
- possibilities to get fresh money
- attraction of the project to international stock exchange markets

- development of the basic market in relation to the development of special markets like telecommunication
- state of the art of alternative systems

Further studies should refine the basic assumptions about these relation between the Economic Environment and the three economic domains $\Sigma_M$ , $\Sigma_C$ , $\Sigma_V$ .

## Market Model

The *Market Model* $\{\Sigma_M, \Re_{EE/M}, \Re_{Services}\}$ links fundamentally the technical and the economic model. This is indeed a very difficult task, because properties of two different domains (engineering, economics) have to be fused properly on an abstract level. The critical link from the technical domain is represented by the relation $\Re_{Services}$. It translates technical functions into market relevant properties denoted by *services*.

Service properties can be derived from the economic purpose of the system under consideration. In our case it is evident, that commercial LEO satellite constellations have to generate revenues by providing satellite-based, mobile communication services. The *Market Model* describes therefore the number of users of such systems as well as the inquired capacity of transferred data per period.

Potential users of such services are:

- business traveller
- Earth exploitation companies
- oil & gas platforms
- airplanes
- ships
- road fleets
- military user.
-

On the basis of available publications of leading market research institutes or future service suppliers [HUB94], [KLOS98], [SZAF93] it was possible to estimate relevant market data for the period from 1999 to 2012 (average number of users, inquired transferred data by *using exponential regressions functions*). Compared with terrestrial mobile communication systems an exponential increase of users seems more realistic than a linear trend.

The number of expected users is shown in Table 1.

| **year** | **global users** [*$10^6$] |
|---|---|
| 1999 | 8,5 |
| 2000 | 9,7 |
| 2001 | 10,9 |
| | |
| 2008 | 25,9 |
| | |
| 2012 | 42,5 |

Tab. 1: Expected users of LEO communication services

The inquired transferred data by the users are modelled with a linear trend (1500 minutes per year in 1999 to 3500 minutes per year in 2012).

Furthermore the following effects are important to estimate the *revenues* of satellite communication systems:

- time of market start
- price (basic rate and price per minute)
- share of the market
- availability
- maximum technical capacity of data transfer
- quality of service

The last point is very important for the revenues of the system. A bad quality or a frequent time out of data transfer or voice communication makes the customers (end users) dissatisfied and dissatisfied users do not generate high revenues (see scenario C in the following paragraph).

## Capital Value Model

The results of the *Cost Model* and the *Market Model* form the basis to establish *the Capital Value Model* $\{\Sigma_V, \Re_{EE/V}, \Re_{LC\_Revenues}, \Re_{LC\_Cost}\}$. Although this model depends on three other domains (as the Market Model does) the situation is much more favourable in this case, because the two pre-domains belong all three to the economics area, which results in more homogeneous and compatible metrics. The *capital value* as the *key economic metrics* is the value of all costs and revenues of an investment project accumulated at the moment $t_0$. The capital value is the only really relevant metrics to compare different systems with economic aspects. The basic mathematical structure of the calculation of the capital value is the following:

$$C_0 = \sum_{t=0}^{T} \frac{(E_t - A_t)}{(1+i)^t}$$

[$c_0$...capital value; t...time, T...last period, E...revenues, A...costs, i...interest rate]

A special topic is the determination of the *interest rate i*. The calculation is based on the *capital assets pricing model* (CAPM). We used the market data of comparable terrestrial telecommunication and existing satellite communication companies (AT&T, Sprint, Deutsche Telekom, Iridium World Comm. Ltd., etc.). The interest rate-model takes also in consideration the effects of taxation and inflation on the success (profit) of the investment project. The concrete calculation of the interest rate yields the result of 8,7325%.

## EXAMPLE

The applicability of the *new techno-economic system model* has been tested in context with a frequently discussed design question in the area of *automation & control*:
*" What is the proper distribution of automation (autonomy) between the space and the ground segment ?".*

The investigation was based on three extreme system scenarios as defined below (Figure 8) [PFOR98] .

- ***Scenario A*** is an example for a system with complex and autonomous satellites (built-in-redundancy at satellite level) and automated ground stations (*maximum autonomy*).
- ***Scenario B*** represents the other extreme, simple satellites with poor onboard autonomy, the satellites have to be operated by human operators in many ground stations. To guarantee the operational status, there are spare satellites installed just from the beginning of service.
- ***Scenario C*** represents a complex and autonomous system similar to scenario A, but the operational status is on an *inferior level*. This scenario is an example for a system with high outage times and allows to study the influence of the customer dissatisfaction.

The used key parameters are listed in Table 2. A detailed functional modelling of the different systems compatible with the key parameters has been performed using available data from [LARS92].

| **Parameter** | **A** | **B** | **C** |
|---|---|---|---|
| Satellites | 48 | 48+8 | 48 |
| earth stations | 2 | 15 | 2 |
| LOC (satellite) | 50 K | 10 K | 50 K |
| satellites per start | 4 | 8 | 4 |
| Availability | 99,9 % | 99,2 % | 80 % |
| market entrance | 2004 | 2002 | 2004 |

Tab. 2: Key parameters of the example scenarios

The basic economic parameters have been chosen identical for all scenarios (e.g. share of the market, prices, interest rate).

## Discussion of Results

A system comparison at cost level, consequently using the *total life cycle costs*

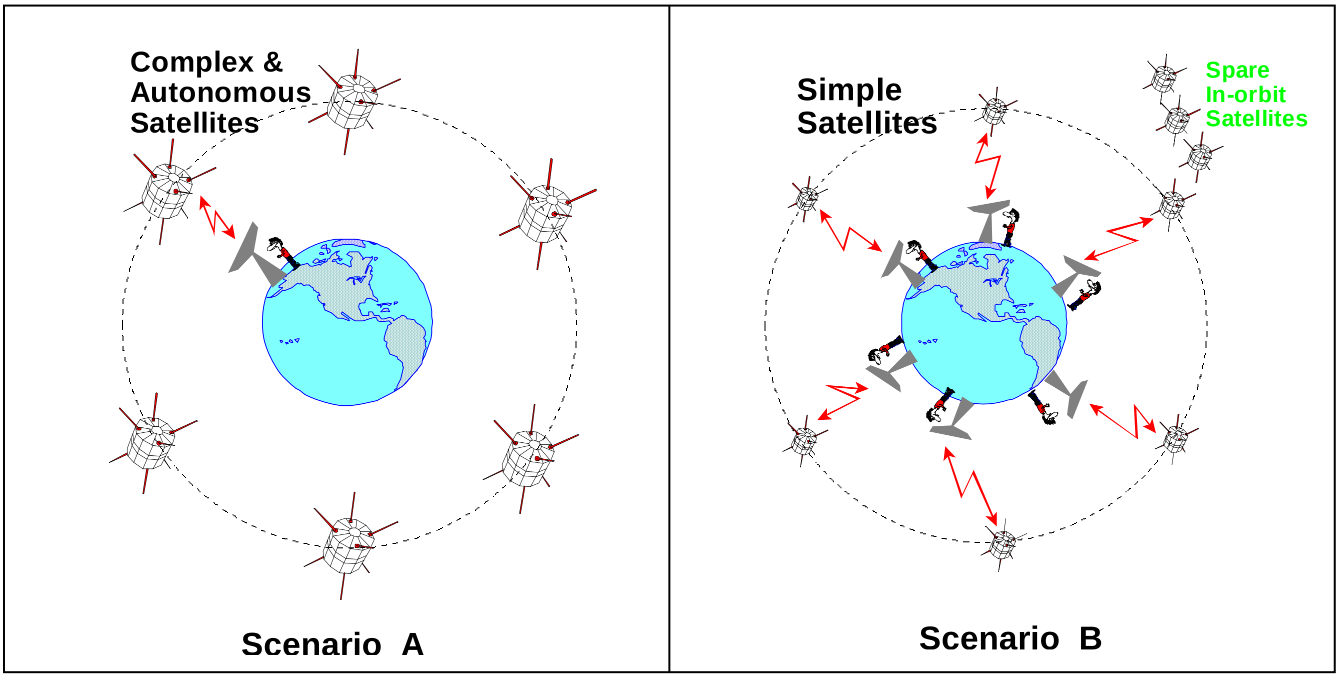
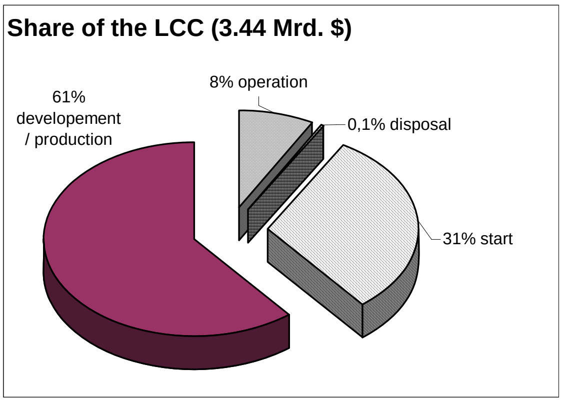


Fig. 8: Example LEO Comsat Constellation



*(LCC)*,

Fig. 9: Share of LCC of system A

shows a *clear advantage* of the *autonomous scenario A* compared to scenario B. The detailed share of the life cycle costs items is shown in Figure 9 (scenario A) and Figure 10 (scenario B). Scenario C has identical costs as scenario A, because differences are found only at the service level.

These results may not be surprising from the automation engineering point of view.

Much more interesting results can be found however, if we have a more complete view on the system in terms of *revenues* and *capital value* (resulting from the Extended Economic Model), shown in Table 3.

The results for Scenario C are quite obvious, due to its degraded service capabilities. The revenues are extremely lower. That is why the effects of the time lags of the service have been modelled with a negative exponential function.

A look on the revenues and capital values reveals however some surprising results.

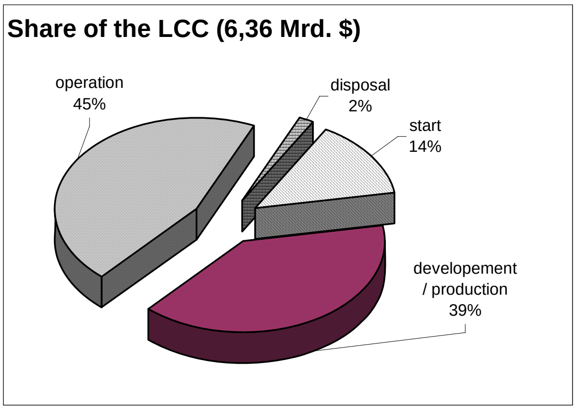
In terms of revenue Scenario B shows some advantage, but looking at the real key metrics *capital value* both scenarios are quasi identical. From this it may be deduced that *Scenario A* seems to be the *best investment project*. It offers the *highest capital value* and the *lowest life cycle costs*. Autonomous satellites and a minimum number of ground stations seem to be the most important design objective for system engineers.

A critical observer would argue, that all these results gained so far might be quite interesting, but the confidence level of the results depends fundamentally on the quality and representativeness of the available design data base. This is completely true and therefore it is good engineering and scientific practice in such a fuzzy situation to validate the results using sensitivity anyalsis techniques.

Fig. 10: Share of LCC of system B

| Scenario | Costs | revenues | capital value |
|---|---|---|---|
| A | 3,44 Mrd.$ | 38,5 Mrd.$ | 15,1 Mrd.$ |
| B | 6,36 Mrd.$ | 41,6 Mrd.$ | 15,0 Mrd.$ |
| C | 3,44 Mrd.$ | 3,6 Mrd.$ | -0,6 Mrd.$ |

Tab. 3: Comparison of the numerical results



The well known principle to derive *sensitivity functions* by building the *partial derivatives* with respect to the *design variables* can be applied in a straightforward manner in our case. Thanks to the existence of a computerised parametric model it is easily possible to vary numerically the design parameters and to get the variation of the outputs.

Figure 11 shows the results of the *sensitivity analysis* for *scenario B*. It is important to realise that revenues (market entrance, share of the market and prices) are the most important economic factor for commercial satellite constellations. The life cycle costs are no cost drivers at all for the capital value (scenario A is half as expensive as scenario B).

The result of a risk analysis shows, that the operation costs of scenario B are spread over the full operational period (10 years). These operations costs are risky to increase over this period (inflation, interests, taxes,...). On the other hand these costs can be influenced during the operation period. The costs of scenario A are not changeable. The life cycle costs of system B could be reduced through automation of the ground stations after the successful (because earlier) start of market service.

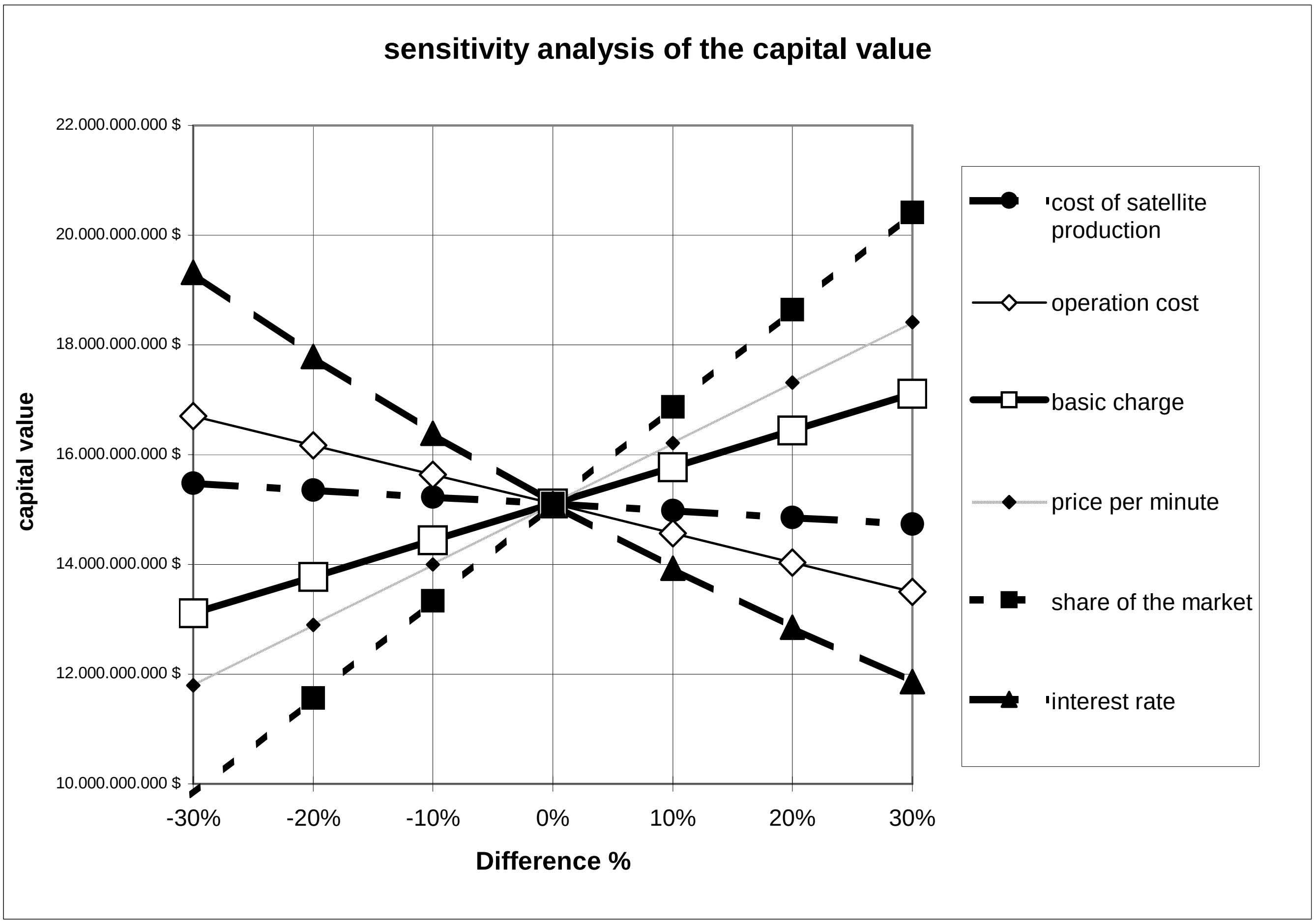


Fig. 11: Sensitivity analysis for the capital value of system B

Taking into account these considerations, it seems to be finally much less risky to choose ***Scenario B*** as ***optimum*** system variant (!).

## FUTURE ACTIVITIES

The existing techno-economic system model is currently adapted and extended for an innovative concept *TrafficEye - Synergetic Use of Satellite-based Navigation, Telecommunication and Earth Observation for Road Traffic Monitoring* [JAN99]. This new concept proposed by Technische Universität Dresden uses a LEO Satellite Constellation to gather realtime road traffic data on the basis of Floating Car Data (received via radio link from road cars) and synchronous satellite imaging information. The optimum system configuration, i.e. the appropriate sharing between terrestrial and satellite resources shall be assessed on the basis of our comprehensive techno-economic model.

## SUMMARY

The proposed modelling approach allows to estimate in a systematic way the complete life cycle costs, i.e. development and operational costs (investment) and operational revenue linked in a systematic to the functional properties of the system. In this sense the model extends in a considerable way the conventional engineering cost models, which consider more or less only certain cost elements.

The paper presents a *functional reference model* (*Structured Analysis Method - SA*) of all elements involved (satellite(s), payload capabilities, ground station, mission control, operating personell, launch) which allows to allocate in a systematic way parametric weights for the technical parameters. A mapping of these parametrized functional models into the physical domain (equipment, element) is based on appropriate reference data bases (e.g. previous projects) and allows the generation of specific metrics, e.g. mass/power/size budgets as well as cost estimates using *Cost Estimating Relationships (CER)*. A complementary *market model*, which is based also on the technical parameters of the LEO constellation, forms the basis for a detailed life cycle cost model incorporating all essential economical mechanisms, e.g. income model, capital investment and capital gains model.

A PC-based prototype implementation of the system model has been performed in a *Microsoft Excel™* environment. The preliminary validation shows a satisfactory correspondence with publically available data for IRIDIUM and GLOBALSTAR and allows sensitivity studies for different scenarios

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