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FRACTIONATED SPACECRAFT ARCHITECTURES SEEDING STUDY

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Final Report

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14. ABSTRACT

The report introduces the concept of spacecraft fractionation, which transforms a traditional monolithic spacecraft into a network of elements where a free-flying payload module is supported by nearby free-flying infrastructure modules supplying communications, data handling, power, etc. Models were developed from a customer-centric perspective to assess different fractionated spacecraft architectures relative to traditional spacecraft architectures using multi-attribute analysis. Along with traditional attributes of mass and cost, non-traditional attributes of maintainability, scalability, flexibility, and responsiveness were included in the assessment. A framework was created to clearly define and evaluate these non-traditional attributes, and appropriate metrics were constructed. This study demonstrates that if those non-traditional attributes are valued enough, customers would choose fractionated spacecraft rather than traditional ones.

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Assessing the Flexibility Provided by Fractionated Spacecraft

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This paper introduces the concept of spacecraft fractionation, which transforms a traditional monolithic spacecraft into a network of elements where a free-flying payload module is supported by nearby free-flying infrastructure modules supplying communications, data handling, power, etc. Models were developed from a customer-centric perspective to assess different fractionated spacecraft architectures relative to traditional spacecraft architectures using multi-attribute analysis. Along with traditional attributes of mass and cost, non-traditional attributes of maintainability, scalability, flexibility, and responsiveness were included in the assessment. A framework was created to clearly define and evaluate these non-traditional attributes, and appropriate metrics were constructed. This study demonstrates that if those non-traditional attributes are valued enough, customers would choose fractionated spacecraft rather than traditional ones.

I. Introduction

Traditional spacecraft are designed for one-time use. They are typically monolithic and have a tailored design. Because of the long development and manufacturing times, designers tend to increase the lifetime of traditional spacecraft and as a result spacecraft tend to grow larger and more complex. This tendency creates large costs and risks associated with a single mission and prevents use of most advanced technologies and reuse of launched elements. Moreover, these traditional architectures have a major drawback in that they limit the possible adaptations of spacecraft to the likely changes in their requirements or environment during their life cycle. The use of modular and standard components was a first step to reduce costs, risks, and development, manufacturing, and testing times. Reconfigurable spacecraft are now being developed to improve flexibility and decrease time constraints. Such new systems are based on standard modules that would be docked and undocked depending on the requirements. Taking modularity a step further means considering a spacecraft made of several smaller building blocks instead of a monolithic one. The technologies recently developed for distributed and cooperative space systems made conceivable this idea of fractionating spacecraft.

The concept of fractionated spacecraft transforms a traditional monolithic spacecraft into a network of elements: a free-flying payload is supported by free-flying modules forming an on-orbit infrastructure. Those modules can be reconfigured, added, or exchanged independently from the others, and be reused over several missions. The lifetime of space assets would be extended by building those reusable and smaller components, which would be a first step toward sustainable space utilization.

II. Spacecraft Fractionation

The concept of spacecraft fractionation transforms a large monolithic spacecraft into smaller modules. This division can be realized in two different ways: homogeneous and heterogeneous fractionation. The originality of the study contained in this paper is that it investigates the latter.

Homogeneous fractionation replaces a large spacecraft with a cluster of smaller identical spacecraft. Those smaller spacecraft are simply scaled-down replicas of the initial spacecraft working in a collaborative manner to achieve an equivalent level of performance. Each of the smaller spacecraft is self-sufficient, can function independently from the others, and is designed in much the same way as traditional spacecraft.

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Heterogeneous fractionation divides the spacecraft into its functional elements. This concept is now conceivable given the technologies being developed for distributed space systems. The payload and its supporting subsystems are implemented in different free-flying modules which all form a single system, as opposed to the system-of-systems resulting from the homogeneous fractionation. This concept makes a clear distinction between the value-added payload and its supporting functions; supporting subsystem functions become reusable on-orbit infrastructure modules and are no longer designed and launched for each payload.

The fractionated spacecraft is presented in Fig. 1 along with the traditional spacecraft. The traditional spacecraft consists of a payload (colored block) and its supporting subsystems (white blocks). The fractionated spacecraft consists of a payload module and infrastructure modules. The payload module contains a payload identical to the one in the traditional spacecraft (colored block) and the supporting functions that are not fractionated (black block). Each infrastructure module (white blocks) is dedicated to a supporting function (power, communications, etc.).

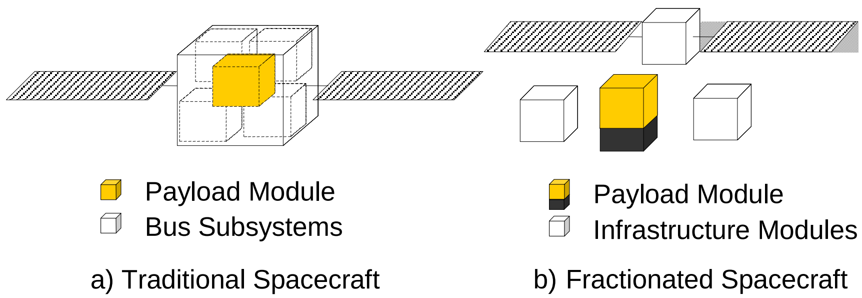


Figure 1. Traditional and Fractionated Spacecraft

The fractionated spacecraft concept turns the dominant integral monolithic spacecraft architecture into a highly modular one, and this modularity offers the fractionated spacecraft many benefits over the traditional one. First, the different subsystems are no longer highly interconnected, therefore they can be developed, manufactured, integrated, and tested in parallel. This functional partitioning combined with the smaller size of the modules, lead to shorter design and build cycles, which means slower obsolescence as more recent technologies can be implemented on the system. Second, the modules can be launched separately which implies fewer spacecraft design constraints imposed by the launcher as well as less financial risk. Third, as the modules can be added, removed, or exchanged independently from the others, the fractionated spacecraft architecture offers much more flexibility, responsiveness, and survivability than the traditional spacecraft. It offers the possibility of on-orbit reconfigurability and significantly modifies the notion of spacecraft lifetime; modules can be developed with different lifetimes as a module's lifetime is no longer dependent on the other subsystems' lifetimes.

III. Assessing the Fractionated Spacecraft Concept

A. Architectures Assessment Method and Criteria

1. Multi-attribute Trade-Space Exploration

The fractionated spacecraft concept is investigated using Multi-attribute Trade-Space Exploration. This method takes a customer-centric approach as it assesses architectures in terms of the attributes valued by possible customers. The attributes taken into account can include traditional ones such as performance, as well as non-traditional ones such as flexibility, and each of them are evaluated independently from the others. The architectures examined are described by a set of design parameters, which forms the design vector. By varying the values of the design parameters, a trade-space of architectures is defined. One of the main advantages of this method is that this trade-space can consist of very different architectures. The exploration of this trade-space allows the assessment of those architectures and analysis of sensitivity to both design parameters and customer needs.

2. Attributes

The attributes chosen as evaluation criteria for this analysis are meant to reflect the value derived from space assets by any potential customer, allow a fair comparison of traditional and fractionated spacecraft in the same trade-space, and significantly vary between the traditional and fractionated spacecraft but also between the various fractionated spacecraft architectures. Thus, in this study, all the systems compared have the same level of performance and are built around the same payload. Therefore, what is measured is the variation in value delivered to the customer by these systems at a constant performance level.

Given that hypothesis of isoperformance, the attributes considered are: mass, maintainability, scalability, flexibility and responsiveness. While mass is a typical attributes of concern to customers of spacecraft systems, the latter four represent non-traditional attributes likely to be valued in a dynamic, uncertain environment. In addition, cost is taken into account as an independent variable.

B. Definition of the Non-Traditional Attributes

The "flexibility" of a complex system can be understood in many different ways and this generic term often encompasses many different kinds of "ilities", from adaptability to scalability. It is crucial in this analysis to clearly define what is meant by those "ilities" before using any as an assessment criterion. A framework that was developed to better understand the differences and similarities between those "ilities" is presented below.

1. A Framework to Analyze the Non-Traditional "ilities" Attributes

Many non-traditional "ilities" attributes can be broadly defined as "the ability of a system to adapt to uncertain internal or external changes affecting its functionality and performance, in a timely and cost-effective manner" [1]. There are different kinds of uncertainties and various ways for the system to adapt to those changes, so that any response to a change can be defined depending on:

1) The nature of the change
2) The nature of the response
3) The time of response

Figure 2 graphically presents this framework.

There are at least two kinds of changes that can occur during a system lifetime: a change in requirements or a change in conditions. A change in requirements can be characterized as either: (a) a change in the functionality required, i.e. the system is required to perform a new function, or the same functional but in a different environment; or (b) a change in the level of performance required, i.e. the system is required to perform the same initial function but with an increased level of performance. A change in conditions may be either internal or external to the system [1]. An internal change may correspond to a component failure or a system failure. An external change may correspond to a change in the environment surrounding the payload or at the interface between the system and its surrounding environment. In some cases, a change may result in changes of other kinds. Each change and how the system adapts to each of them must then be analyzed sequentially.

The response to an initially unexpected change can be of two kinds: active or passive. The passive response can be understood as a tolerance of the system to change and is often linked to the concept of robustness. The possible active responses tend to be system-specific. Possible adaptations with a fractionated architecture consist of: reconfiguration, subtraction, addition, or exchange of elements.

The response of the system to a change can take place within different timeframes. This leads to different kinds of adaptations to the change depending on the importance given to the time factor. Three timeframes are defined in this framework: short-, medium- and long-terms. These timeframes are all relative and depend mainly on the system and user perspective.

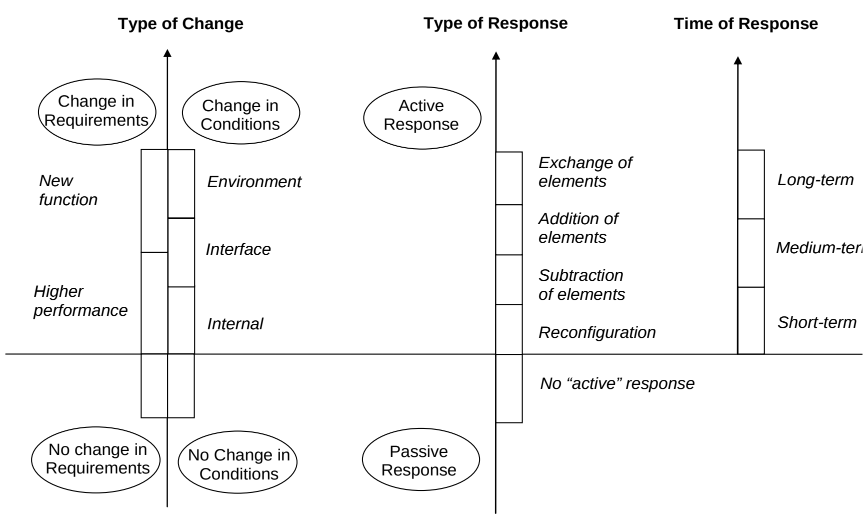


Figure 2. Framework to Define the Different Kinds of "Flexibility"

2. Definition of the Attributes

Each attribute used in this analysis can be defined using this framework, as shown in Table 1.

- *Maintainability* can be defined as the "ability of a system to be kept in an appropriate operating condition" [3], which corresponds in the framework to a change in internal conditions leading to an exchange of element(s).
- *Scalability* can be defined as the "ability of a system to maintain its performance and function, and retain all its desired properties when its scale is increased greatly without having a corresponding increase in the system's complexity" [3]. This corresponds in the framework to a change in requirements, namely an increased performance level.
- *Flexibility* can be defined as the "ability of the system to be modified to do jobs not originally included in the requirements definition" [4]. This would correspond in the framework to a change in requirements, namely a change in function, which would require an active response.
- *Responsiveness* can be defined as the ability to meet changing requirements quickly, which corresponds in the framework to a short- or medium-term adaptation to any change in requirements.

	Change in requirements			Change in conditions				Type of response					Time of response		
	No change	Higher performance	New function	No change	Internal	Interface	Environment	No active response	Reconfiguration	Subtraction of elements	Addition of elements	Exchange of elements	Short- term	Medium-term	Long-term
Maintainability	X				X							X	X	X	X
Scalability		X		X					X		X	X	X	X	X
"Flexibility"			X	X					X	X	X	X	X	X	X
Responsiveness		X	X	X					X	X	X	X	X	X	

Table 1. Definition of the Attributes

IV. Fractionated Spacecraft Architectures and Fractionation Strategies

1. Design Parameters

At the spacecraft level, the design parameters describing the architectures examined are:

- The subsystems fractionation level
- The technologies taken into account
- The number of infrastructure modules
- The subsystems contained in these modules

In a fractionated architecture, the supporting functions provided by the traditional spacecraft bus are distributed between the payload module and the infrastructure modules. A level of fractionation, from 0 to 100%, can then be defined for each subsystem, representing the distribution of this function between the module dedicated to that function and the rest of the modules. The subsystems considered as potentially "fractionable" in this study are the communications, control and data handling, power, attitude determination and control, and propulsion subsystems.

A fractionation level can also be defined at the spacecraft level, and can characterize the degree of fractionation of the spacecraft architectures relative to each other. This spacecraft fractionation level has two main dimensions. The first is the supporting function distribution between the payload and the infrastructure, and the second is the number of physically separate infrastructure modules.

Distribution of the supporting functions between the payload and the infrastructure is linked to the technologies considered. Several subsystems are considered "fractionable", but some are more easily "fractionable" and it seems logical to fractionate some subsystems before others. Therefore, various sequences of subsystem fractionation that evolve a traditional spacecraft to a totally fractionated spacecraft can be defined. The one chosen in this study is based on today's technology maturity level and is presented in Fig. 3. The focus is not on a particular technology but more on a capability that could be reasonably implemented using different technologies.

The 0% fractionation level corresponds to the traditional monolithic spacecraft. In the first step of the fractionation process, the possibility of wireless data transmission is considered, which leads to the complete fractionation of both the communications and the control and data handling subsystems. For the purposes of this study, the fractionation level of these two subsystems modules is either 0 or 100%. In the second step, the possibility of beaming power is considered, but this time the fractionation can be partial, on a continuum from 0 to 100% of fractionation, and two different approaches are taken into account: either both the power generation and storage function are fractionated at the same time, or the power generation is entirely fractionated in the power module and only the storage is distributed between the power module and the other modules. Finally, the possibility of collaborative separated positioning is considered, which would lead to the complete fractionation of both the attitude determination and control and the propulsion subsystems.

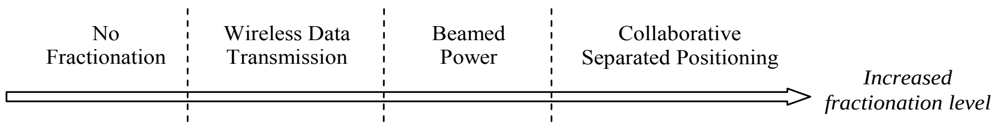
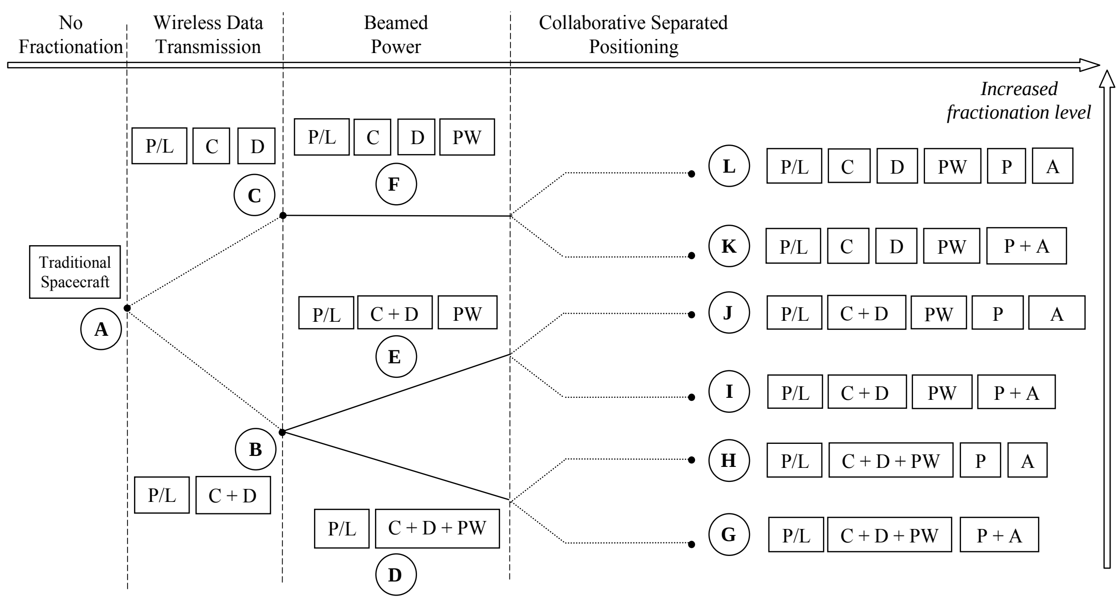


Figure 3. Fractionation Technology Axis

The second dimension of fractionation at spacecraft level concerns the number of separate modules that form the infrastructure architecture. As the infrastructure can consist of more or fewer modules, this number gives another measure of the spacecraft fractionation level.

2. Architectures Matrix

A matrix of the possible architectures can then be built using those two dimensions as shown on Fig. 4. Each box represents a module, and each architecture is labeled with a circled letter from A to G. The architectures can be ranked from the least to the most fractionated, i.e. from architecture A to architecture L. Fractionation strategies can be defined as the different paths along the technology axis, from the traditional spacecraft architecture to one of the most fractionated architectures, i.e. architectures G through L. As mentioned above, only architectures D, E, and F correspond to a continuum along the fractionation paths and are represented by plain lines, whereas the other architectures are represented by dots artificially linked with dotted lines.



Modules *P/L Payload* *C Communications* *D Control and Data Handling*
PW Power *P Propulsion* *A Attitude Determination and Control*

Figure 4. Architectures Definition Matrix

V. Models

A. Mass Model

In the mass model, all the architectures are based on identical payloads defined by their mass and power requirements. Given a payload, the first step of the model is to size the corresponding traditional spacecraft. The supporting subsystems are sized using mass ratios and power ratios. Different mass ratios are used depending on the mission application. Three main types of missions are investigated: navigation, communications, and sensing.

In the model, when a subsystem is fractionated, it is taken out of the spacecraft as it is and becomes the "payload" of a new module. For instance, when the communications subsystem is fractionated, it becomes a communications module with its own power, propulsion, attitude control, and thermal subsystems. The mass ratios are used to size the subsystems of this new module and the power ratios are used to size the power required by these subsystems, given the initial power requirement of the subsystem.

Additional masses and power due to wireless data transmission, power beaming, or collaborative separated positioning are added. For instance, the power module has additional mass and power to beam power to all the other modules and compensate for the losses. They have been modeled as percentages of the masses or powers of the sizing subsystems. For instance, the mass of the wireless data exchange subsystem of the communications module is defined as a percentage of the mass of the communications subsystem. Various technologies have been examined and sensitivity analyses have been run on these parameters.

For comparability purpose, the traditional spacecraft and all the fractionated spacecraft modules are assumed to be designed for the same lifetime, even though one advantage of the fractionation is that modules can be designed with different lifetimes.

The expected results of the mass model are presented in Fig. 5. The different architectures and fractionation strategies defined in Fig. 3 are identified by circled letters. Because of the mass model structure, the mass penalty, defined as a percentage of the traditional spacecraft mass, is independent from the mass and power of the payload.

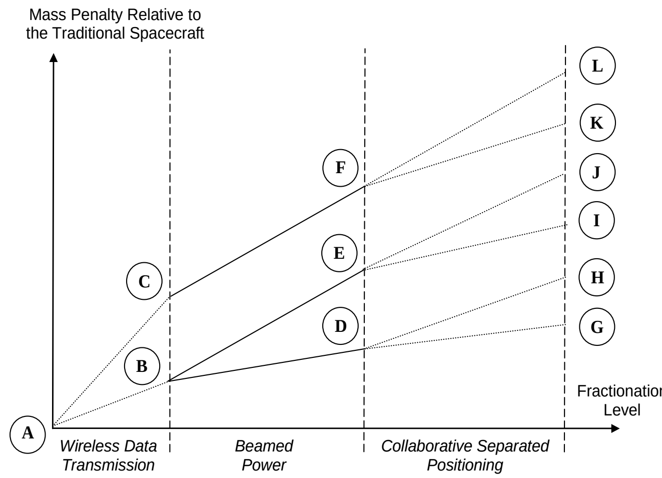


Figure 5. Spacecraft Mass Increase due to Fractionation

B. Cost Model

The cost model is built using cost estimating relationships based on subsystem masses [6]. A traditional spacecraft cost model, as opposed to a small satellite cost model, is used for both the traditional and the fractionated spacecraft for comparability purpose and because, despite commonalities, the small satellite paradigm remains very different from the fractionated spacecraft one. Nevertheless, traditional cost models can be reasonably considered as unfavorable to the fractionated spacecraft as significant cost reductions are expected, even at spacecraft level, for instance on assembly, integration, and test costs.

C. Attributes Evaluation

Maintainability, scalability, and flexibility are measured in monetary units, whereas responsiveness is measured in units of time.

1. Maintainability

To evaluate architecture maintainability, the following scenario is defined. An internal failure occurs in a subsystem. For fractionated architectures, the module containing the corresponding subsystem is assumed to be exchanged with an identical one. For the traditional architecture, a whole identical spacecraft is assumed to be exchanged. The manufacturing cost of a new identical module relative to the cost of manufacturing a new traditional spacecraft is used as a maintainability metric.

2. Scalability

To evaluate architecture scalability, a new scenario is defined. An increased level of performance is required from the spacecraft, which corresponds to a larger payload requiring more power. For fractionated architectures, the payload module is exchanged with a new one. The new module has increased performance in the payload but it is assumed that its subsystems are sized to compensate for the difference between the new payload requirements and the existing infrastructure modules. For instance, the additional power required by this increased performance payload is not provided by an additional infrastructure power module, but by the new payload module itself. This hypothesis reflects the focus of this study on heterogeneous fractionation. Adding an additional power module to compensate for the additional power required would correspond to a homogeneous fractionation approach. However a combination of heterogeneous and homogeneous fractionation is certainly promising in terms of spacecraft scalability and survivability and should be further examined. The new payload module and its equivalent increased-performance traditional spacecraft require a limited new development effort proportional to the increased performance. The costs of this development effort and of the payload module manufacturing relative to the equivalent costs for a traditional spacecraft is used as a scalability metric.

3. Flexibility

To evaluate architecture flexibility, a third scenario is defined. A new function is required from the spacecraft. To distinguish this scenario from the scalability scenario, it is assumed that the new payload has similar requirements as the initial one, so that the initial infrastructure modules can be reused as such. For fractionated architectures, the payload module is exchanged with a newly developed one. For the traditional architecture, the spacecraft is exchanged with a whole newly-developed one. The payload module new development and manufacturing costs relative to the equivalent costs for a whole traditional spacecraft is used as a flexibility metric.

4. Responsiveness

Architecture responsiveness is assessed using the same scenario as the one used for flexibility. Responsiveness in this example is associated with the time necessary to get a new function delivered, and therefore with the time necessary to exchange the payload module or the whole spacecraft with a new one. The time necessary to develop and manufacture a new payload module relative to the equivalent time for a whole traditional spacecraft is used as a responsiveness metric.

VI. Results

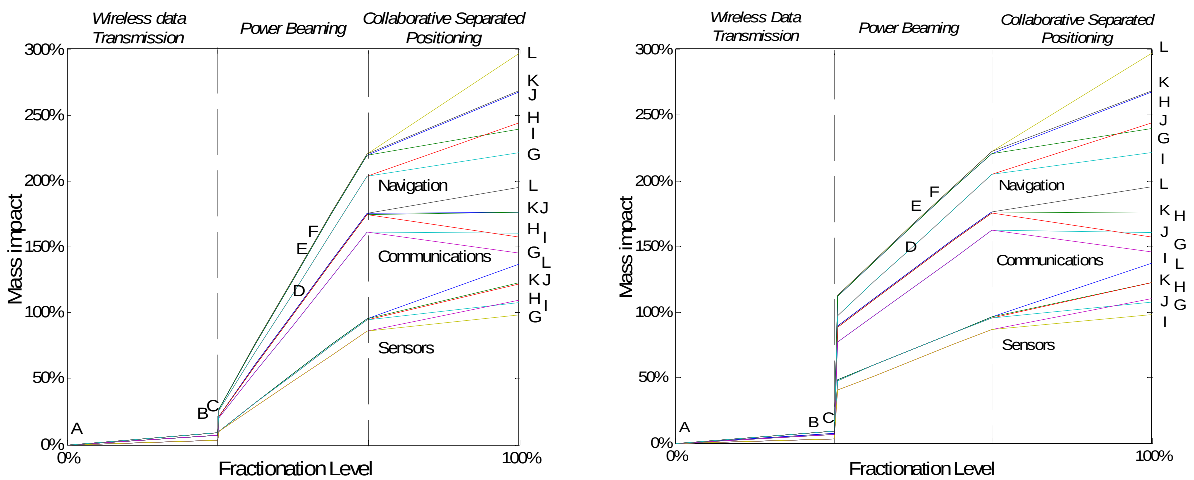
A. Impact of the Fractionation on the Spacecraft Total Mass

One of the expected drawbacks of the spacecraft fractionation is a mass penalty. The mass model quantifies this penalty for all the fractionation strategies. Figure 6 presents the mass penalty as a percentage of the traditional spacecraft mass for each of the fractionated architectures applied to three types of space missions. Figures 6 a) and b) correspond to the two power subsystem fractionation strategies discussed in Section IV.

As expected, the mass tends to increase with the fractionation level along the x axis. There is a clear difference in mass penalty depending on the mission. The navigation mission has the largest mass penalty, which varies between 220% and 300%, whereas the sensing mission has the smallest one, which varies between 100% and 140%. Again, in this model the variation in mass penalty among mission types is due to the modeled differences in subsystem mass ratios based on historical tendencies for these three types of space missions.

A remarkable feature is the step up in mass penalty that occurs at the fractionation of the power subsystem, which is due in case a) to the additional hardware required to transmit and receive power, and in case b), in addition to this hardware, to the complete fractionation of the power generation function into the power module. The only differences between the two power subsystem fractionation strategies occur in the continuous fractionation of the power subsystem, i.e. in the middle third of Figure 6a) and 6b).

As mentioned above, the mass tends to increase with the fractionation level. One can notice that in some cases the total system mass decreases with the fractionation of the attitude control and propulsion subsystems in the final third of Figure 6a) and 6b). When this fractionation occurs, one or two new modules are created, but the attitude control and propulsion functions are taken out of all the other modules and centralized. The difference between those two effects, which are opposite in terms of mass impact, leads in those cases to a decrease in the total system mass; the mass decrease resulting from the concentration of those functions is larger that the mass increase due to the addition of new modules.



a) Simultaneous Fractionation of the Power Generation and Storage Functions

b) Total Fractionation of the Power Generation Function and Progressive Fractionation of the Power Storage Function

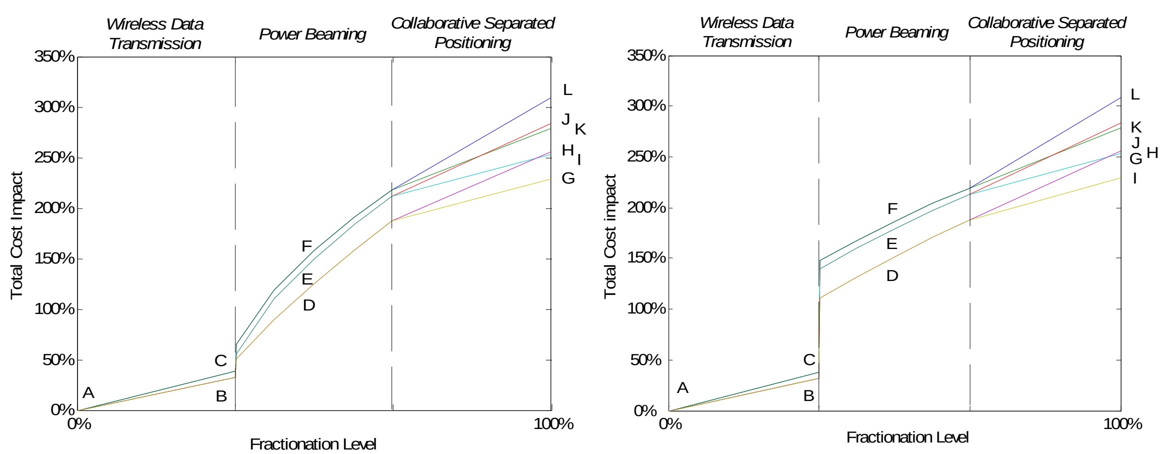
Figure 6. Mass Penalty Due to Fractionation for Different Fractionated Architectures

B. Impact of the Fractionation on the Spacecraft Cost

Another expected drawback of the spacecraft fractionation, linked to the mass penalty, is a cost penalty. The cost model quantifies this penalty for all the fractionation strategies. Figure 7 presents the cost penalty as a percentage of the traditional spacecraft cost for the all the fractionated architectures applied to a communications mission. Fig. 7 a) and b) correspond to the two power subsystem fractionation strategies.

In a way similar to what is described above for mass, the differences between the two power subsystem fractionation strategies occur in the continuous fractionation of the power subsystem. One can notice that the cost always increases with the fractionation level along the x axis. This is in contrast to the mass penalty graphs given in Figure 6a) and 6b), which for some architectures show a decrease in mass in the final stage of fractionating the attitude control and propulsion subsystems.

If the three types of missions are compared for the most fractionated architectures, the cost penalty is again the largest for navigation spacecraft, for which it varies between 270% and 350%, and the smallest for sensing, for which it varies between 190% and 250%.



a) Simultaneous Fractionation of the Power Generation and Storage Functions

b) Total Fractionation of the Power Generation Function and Progressive Fractionation of the Power Storage Function

Figure 7. Cost Penalty Due to Fractionation for Different Fractionated Architectures Applied to a Communications Mission

C. Impact of the Fractionation on the Spacecraft "Flexibility"

1. Maintainability

Two examples for a communications mission are presented to illustrate the maintainability metric. In these examples, the power fractionation strategy in which both the power generation and storage functions are fractionated simultaneously is the one assumed.

The first example assumes a complete failure of the communications subsystem. If the spacecraft has a fractionated architecture, only the module that contains the communications subsystem has to be exchanged, whereas if it has a traditional architecture, a whole new spacecraft is assumed to be needed.

Figure 8 presents the mass ratio between the module that contains the communications subsystem and the traditional spacecraft. This ratio is expected to get smaller as the fractionation level increases. In fact, the ratio does get smaller for the architectures in which the communications subsystem is not located in the same module as the power subsystem, i.e. architectures I through L. For architectures K and L, the mass ratio becomes as small as 7%. If the communications subsystem is in the same module as the power subsystem, as in architectures G and H, this module becomes larger than the traditional spacecraft itself as the fractionation level increases. This result highlights the important and often driving role played by the power subsystem in fractionated architectures.

More representative of architecture maintainability is the cost ratio between the module that contains the communications subsystem and the traditional spacecraft, which is presented on Fig. 9. It is a ratio between recurring costs, as the module is assumed to be exchanged with an identical one. The same difference as the one identified on Fig. 8 between architectures G and H and the others is noticeable. The lower the cost of the communications module relative to the cost of the whole spacecraft, the more maintainable the architecture is in case of communications subsystem failure. For architectures I through L, the communications module cost is lower than 30% of the traditional spacecraft cost.

The second example looks closer at the particular case of the power module. It assumes a complete failure of the power subsystem. In the same way as in the first example, if the spacecraft has a fractionated architecture, only the module that contains the power subsystem has to be exchanged, whereas if it has a traditional architecture, a whole new spacecraft is assumed to be needed.

Figure 10 presents the mass ratio between the module that contains the power subsystem and the traditional spacecraft. On the left third of the figure, the module that contains the power subsystem is the payload module. Then, as the fractionation level increases, the power fractionated is either, like in architecture D,

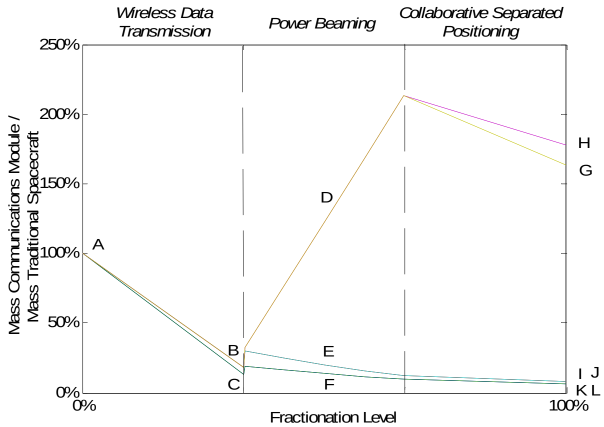


Figure 8. Mass of the Communications Module to be Exchanged Relative to the Traditional Spacecraft Mass

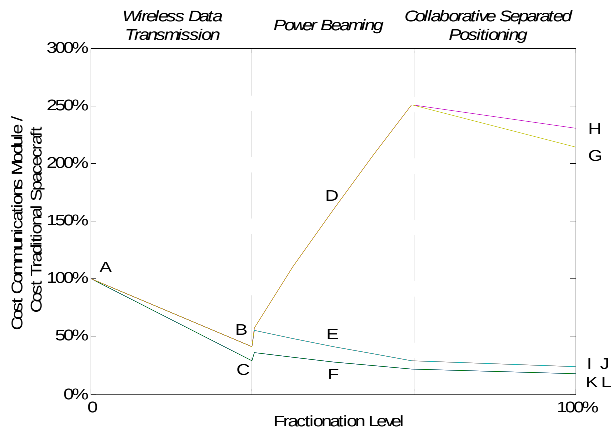


Figure 9. Cost of the Communications Module to be Exchanged Relative to the Traditional Spacecraft Cost

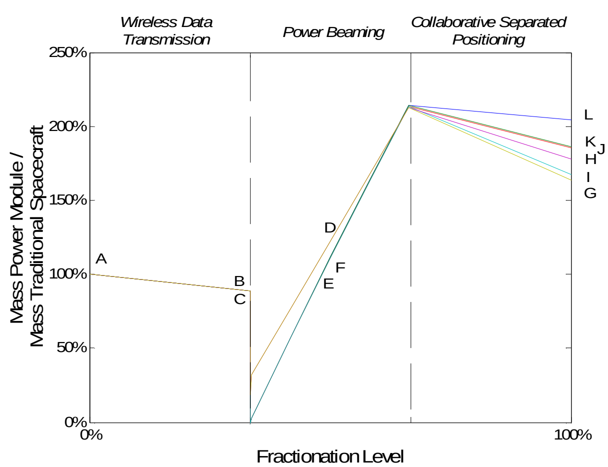


Figure 10. Mass of the Power Module to be Exchanged Relative to the Traditional Spacecraft Mass

added to the communications and data handling module, or a new power module is created, like in architectures E and F. This difference explains the step when the power starts getting fractionated in the case of architecture D.

The major impact of the power subsystem on the fractionation results becomes obvious in Fig. 10. For all the architectures, as the power fractionation increases, the power module becomes heavier than the initial traditional spacecraft.

An interesting feature is that the architectures in which the power subsystem is not fractionated in its own module, i.e. architectures G and H, are not the ones with the largest power module. Again, this illustrates two opposite effects. When the power subsystem gets fractionated in its own module, as opposed to when it gets fractionated in the communications and data handling module, the power module does not contain any other subsystem, so it should be lighter, but it has to generate extra power to beam power to the communications and data handling module(s), which makes it heavier.

The ratio of costs is shown on Fig. 11. Again, for all the architectures, as the power fractionation increases, the power module becomes more expensive than the initial traditional spacecraft. This means that with the traditional spacecraft mass ratios and cost relationships, fractionation would not make the spacecraft more maintainable in case of failure of the power subsystem.

This second example illustrates that when considering technology development to improve fractionated spacecraft design the main focus should be on power subsystems.

2. Scalability

The scenario chosen to assess the scalability of the architectures focuses on the payload. Therefore, the major differences in the results are between the three kinds of missions. The example presented to illustrate the scalability metric assumes the need for a new higher-performance payload that would be 30% heavier than the initial one and that would require 30% more power. If the spacecraft has a fractionated architecture, only the payload module has to be exchanged, but if it has a traditional architecture, a whole new spacecraft is assumed to be needed.

Figure 12 presents the mass ratio between this new payload and the corresponding traditional spacecraft. At complete fractionation, the communications mission has the smallest payload module that weights about 45% of the traditional spacecraft. The sensing mission has the largest one which weights about 57% of the traditional spacecraft.

Figure 13 shows the cost ratio between the scaled-up payload module and the corresponding traditional spacecraft. The costs include a limited development effort to scale-up the system as well as recurring costs.

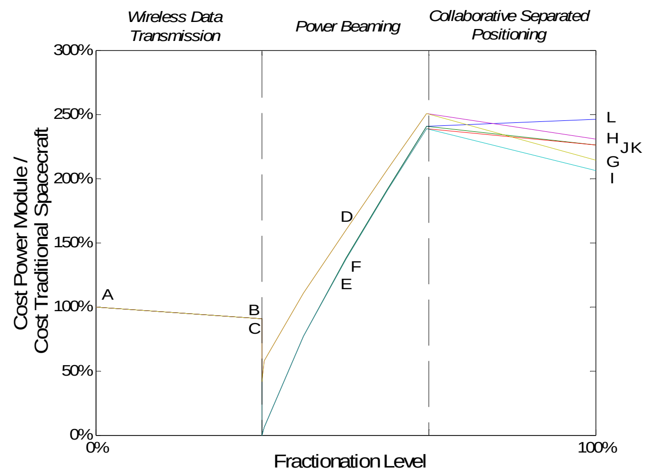


Figure 11. Cost of the Power Module to be Exchanged Relative to the Traditional Spacecraft Cost

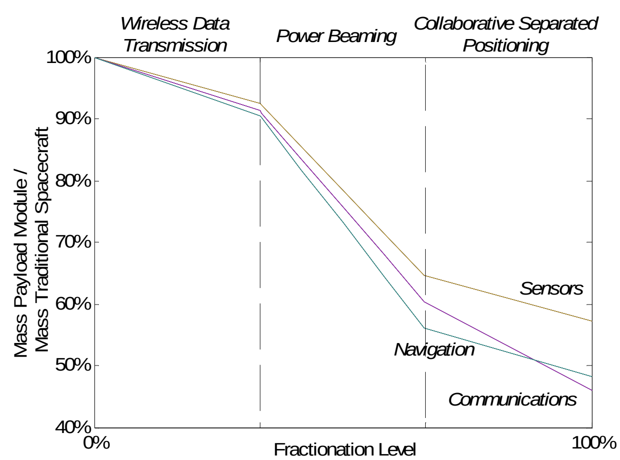


Figure 12. Mass of the New Payload Module Relative to the Traditional Spacecraft Mass

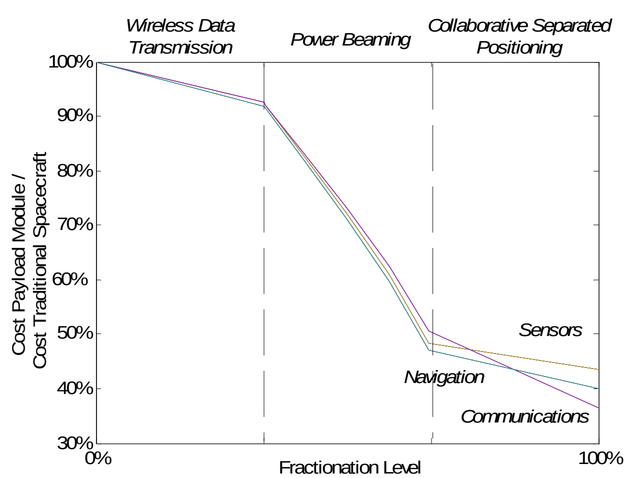


Figure 13. Cost of the New Payload Module Relative to the Traditional Spacecraft

For the more fractionated architectures, a communications mission payload module costs less than 40 % of the traditional spacecraft cost, which corresponds to significantly improved scalability for fractionated spacecraft over traditional spacecraft.

3. Flexibility

As in the scalability assessment, the scenario chosen to assess the flexibility of the architectures focuses on the payload, and the major differences in the results are between the three kinds of missions. The example presented to illustrate the flexibility metric assumes the need for a new function, which means a new payload. It is assumed that the new payload requires a whole new development effort. Again, if the spacecraft has a fractionated architecture, only the payload module has to be exchanged, but if it has a traditional architecture, a whole new spacecraft is assumed to be needed.

Figure 14 presents the mass ratio between this new payload and the corresponding traditional spacecraft. At complete fractionation, the communications mission has the smallest payload module that weights about 30% of the whole spacecraft. The sensing mission has the largest one which weights about 45% of the whole spacecraft.

Figure 15 shows the cost ratio between the newly-developed payload module and the corresponding traditional spacecraft. The costs include a complete new development effort as well as recurring costs. For the more fractionated architectures, a communications mission payload module costs less than 25% of the whole traditional spacecraft cost, which corresponds to significantly improved flexibility for fractionated spacecraft.

4. Responsiveness

The scenario chosen to assess architecture responsiveness is the same as the one used for flexibility.

Figure 16 shows the ratio between the time necessary to develop, manufacture, integrate, assemble and test a new payload module and the time necessary for a whole traditional spacecraft. Again, this ratio depends mainly on the kind of mission.

The communications missions have the shortest cycle for the most fractionated architectures, at almost 30% of the traditional spacecraft.. This result is based on the hypothesis that the fractionated spacecraft will have comparable development, manufacturing, integration, and test cycles as a traditional spacecraft, which is unfavorable to the fractionation concept even when looking at just the payload module.

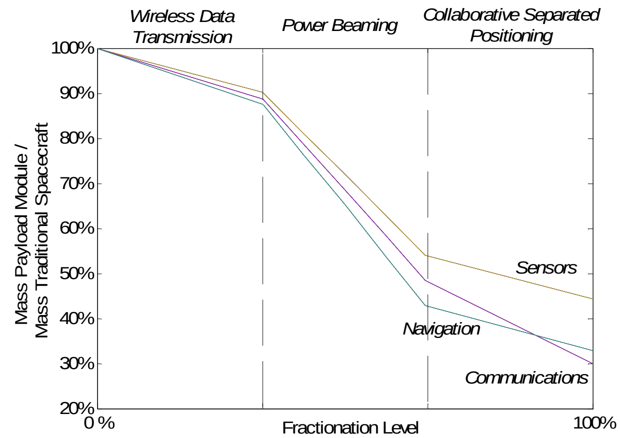


Figure 14. Mass of the New Payload Module Relative to the Traditional Spacecraft Mass

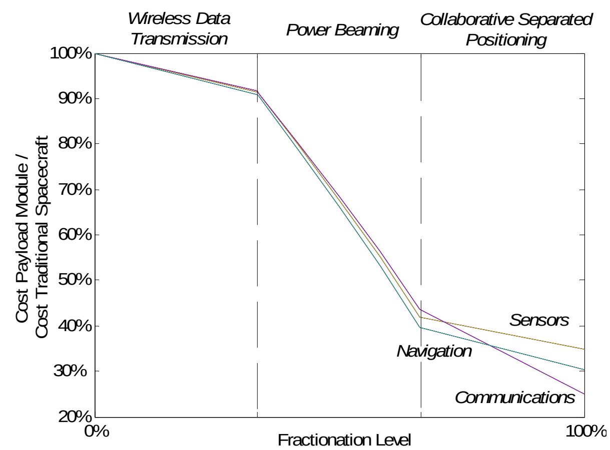


Figure 15. Cost of the New Payload Module Relative to the Traditional Spacecraft Cost

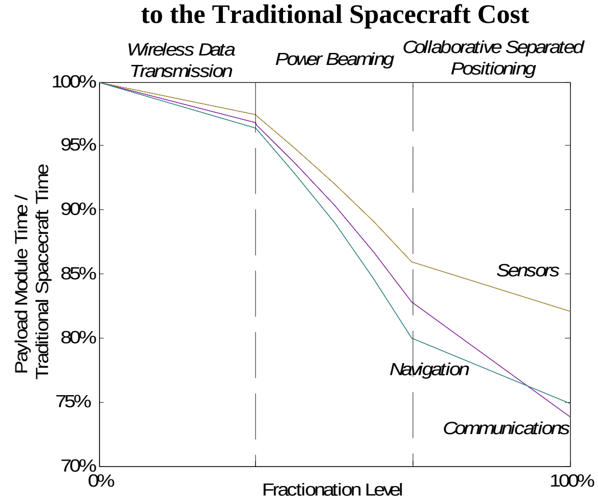


Figure 16. Time Necessary for the New Payload Module Relative to the Time Necessary for the Traditional Spacecraft Cost

VII. A New Fractionated Spacecraft Paradigm

The first results of this study show that the concept of fractionated spacecraft can provide customers with more flexible space capabilities at limited costs. The approach to model masses and costs of the fractionated architectures reflects the traditional spacecraft paradigm and are therefore rather unfavorable to the fractionation concept. Indeed, the spacecraft fractionation concept creates its own new paradigm, especially when viewed from a whole on-orbit infrastructure perspective. One can imagine building a whole on-orbit infrastructure of standardized modules to support different payloads. Today's prototype approach would become a mass production approach, and a more modular architecture made of smaller modules could prompt sweeping changes to the space industrial base structure. The industry would gain new dynamics, become much more competitive, and much less stable and concentrated, as described by Baldwin in [7]. The shorter cycles would set a faster pace and new opportunities would be created more frequently.

Thus the mass and cost penalties presented in this paper may reasonably be considered as a worst case scenario if the technologies necessary for fractionation are improved. There are obviously significant risks associated with fractionated architectures, especially technical ones, but there are also many advantages and possible synergies with other concepts for improving the sustainability of space utilization, such as homogeneous fractionation or on-orbit servicing. This paper begins to demonstrate the idea that if non-traditional attributes are valued enough, customers would choose fractionated spacecraft rather than traditional ones. But despite so many potential benefits, there are still major barriers to the shift from today's paradigm to the new fractionated spacecraft paradigm, which would require the exploration of potential policy options to enable such a transition.

VIII. Future Work

While this paper focuses on the fractionation of a single spacecraft, the next phase of the study will investigate the aggregate infrastructure on orbit formed by the supporting modules of several fractionated spacecraft, and will similarly explore and assess different aggregate infrastructure architectures in terms of traditional and non-traditional attributes. The paradigm shift and the policy options to make this shift possible will also be further studied.

Acknowledgments

The authors wish to thank Dr. Owen Brown and Paul Eremenko for their insights and feedback, as well as the Defense Advanced Research Projects Agency (DARPA) for supporting the work that made this paper possible.

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II. Accompanying presentation for paper presented at the AIAA Space 2005 Conference, September 2005, Long Beach, California.

Space 2005

August 31st 2005

Assessing the Flexibility Provided by Fractionated Spacecraft

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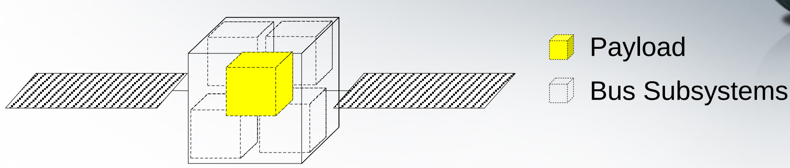
Agenda

- Fractionated Spacecraft Definition
- Architectures Assessment Method
- Results of the Architectures Evaluation
- Conclusions and Follow-On
- Questions

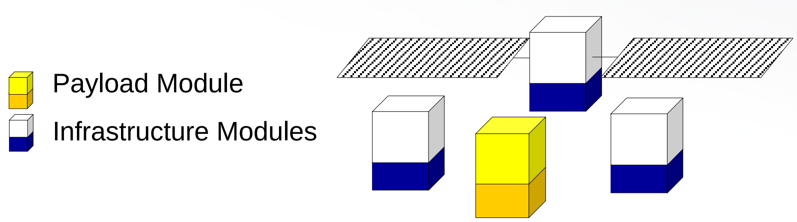
A Definition for the Fractionated Spacecraft

- Transforms the traditional monolithic spacecraft into a network of elements
- A free-flying payload is supported by an on-orbit infrastructure composed of several free-flying modules

From the Traditional Spacecraft



To the Fractionated Spacecraft



Multi-Attribute Trade-Space Exploration

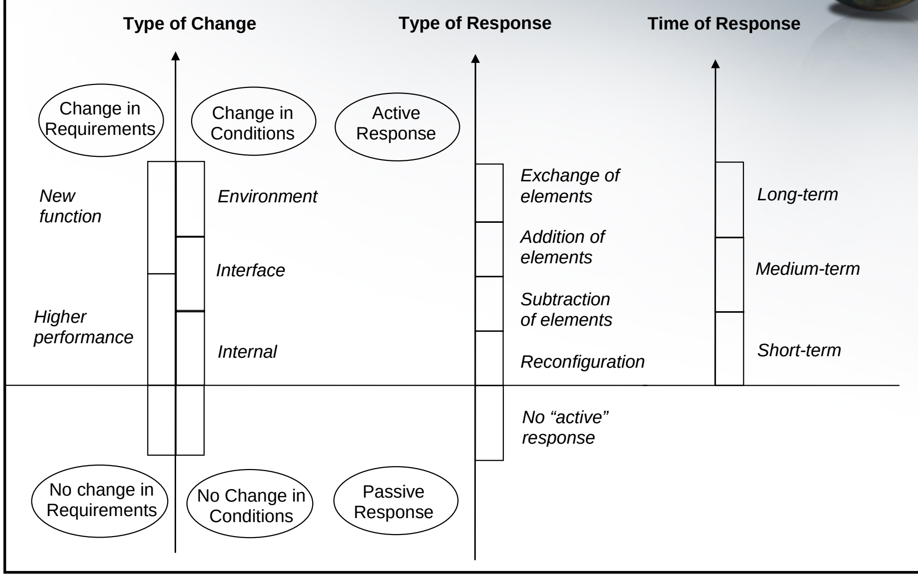
1. Definition of the Attributes valued by Potential Customers
2. Definition of the Design Parameters
3. Definition of the Design Vector
4. Evaluation of the Architectures Attributes and Sensitivity Analyses

Architectures Assessment using Traditional and Non-traditional Attributes

Fractionated and traditional architectures are assessed at isoperformance in terms of:

- Traditional attribute
  - Mass Impact
- Non-traditional attributes
  - Maintainability
  - Scalability
  - Flexibility
  - Responsiveness

A Framework to Define Non-Traditional Attributes



Definition of the Non-Traditional Attributes Used

	Change in requirements			Change in conditions				Type of response					Time of response		
	No change	Higher performance	New function	No change	Internal	Interface	Environment	No active response	Reconfiguration	Subtraction of elements	Addition of elements	Exchange of elements	Short- term	Medium-term	Long-term
Maintainability															
Scalability															
"Flexibility"															
Responsiveness															

Design Parameters (I/II)

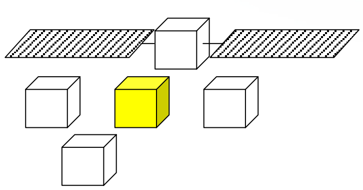
Fractionation Design Parameters

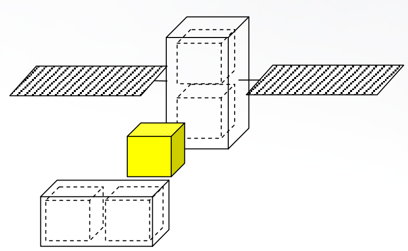
- Fractionated supporting functions
  - Communications
  - Control and Data Handling
  - Power
  - Attitude Determination and Control
  - Propulsion
- Power Function Fractionation Level
- Type of Power Fractionation

Design Parameters (II/II)

Infrastructure Architecture Design Parameters

- Number of infrastructure modules
- Functions within each module





Spacecraft Fractionation Level

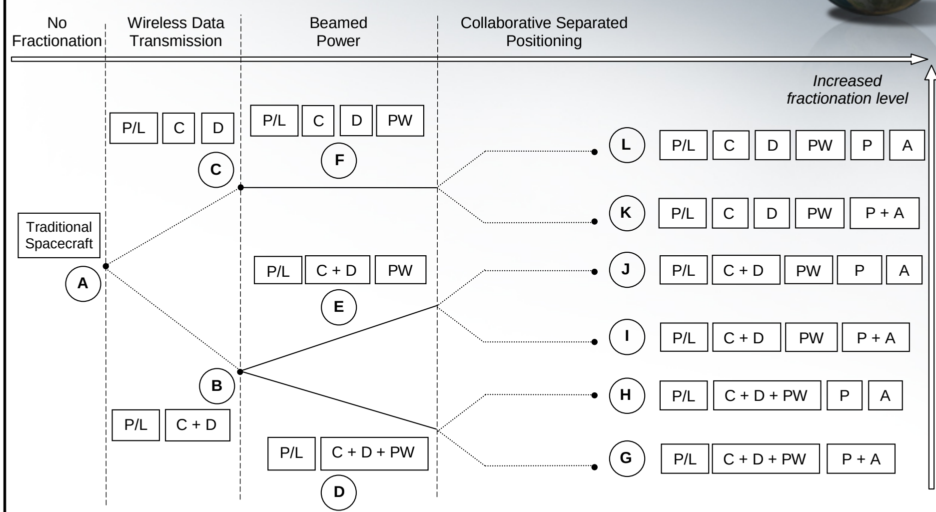
Two Main Fractionation Dimensions

- Technologies Considered and Functions Fractionated

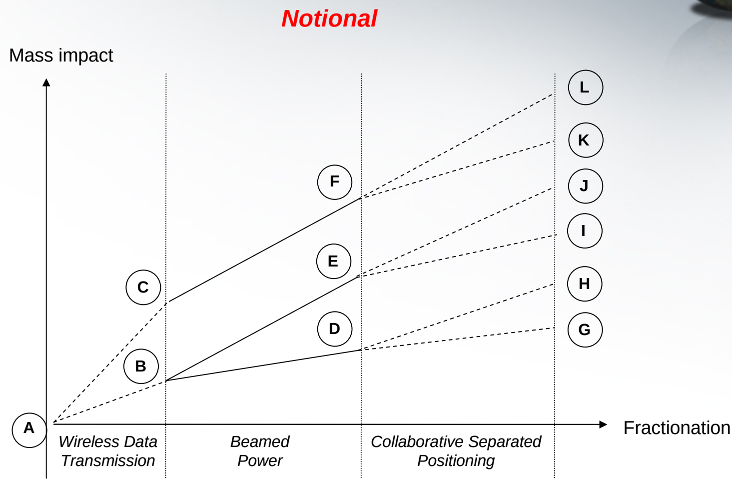
Capability	None	Wireless Data Transmission	Beamed Power	Collaborative Separated Positioning	*Increased fractionation level*
Fractionated Functions	No Fractionation	⇨Communications ⇨Control and Data Handling	⇨Power	⇨Attitude Determination and Control ⇨Propulsion	

- Number of Infrastructure Modules

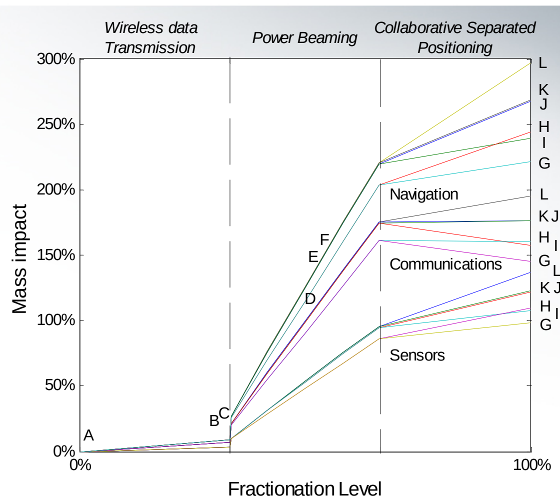
Fractionated Spacecraft Architectures



Fractionation Strategies and Mass Impact of the Fractionation



Fractionation Mass Impact



➩ *Mass Often Increases with Fractionation, but Sometimes Decreases*

Two Opposite Effects of the Fractionation on the System Mass

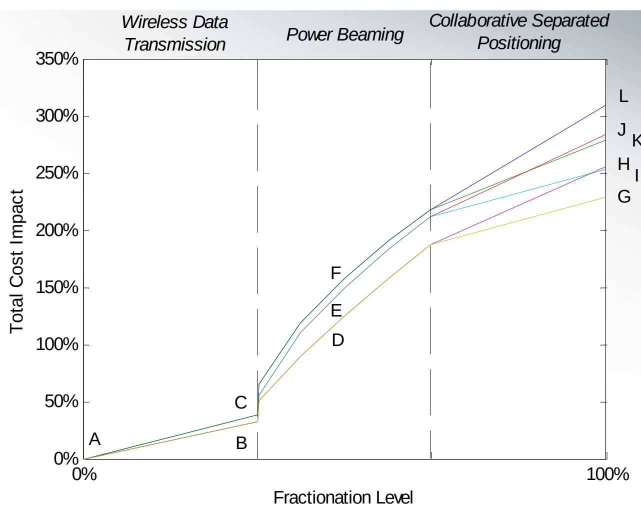
Mass Increases when a Function is Fractionated

Mass Decreases when a Function is Fractionated

Increased Number of Modules

Centralization of the Supporting Function

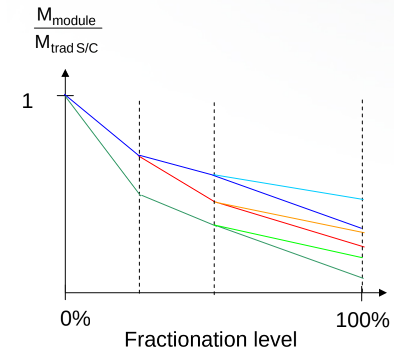
Fractionation Cost Impact



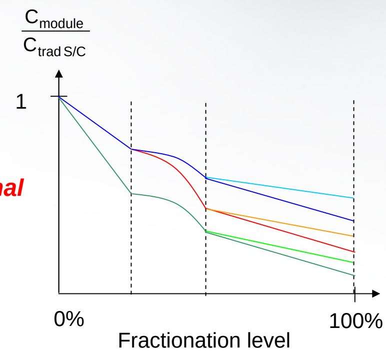
⇨ *Cost Always Increases with Fractionation*

Maintainability Assessment

Attribute	Change	Module concerned	Type of module	Units
Maintainability	Complete Internal Failure	Infrastructure Module	Same module (Previously developed)	Monetary



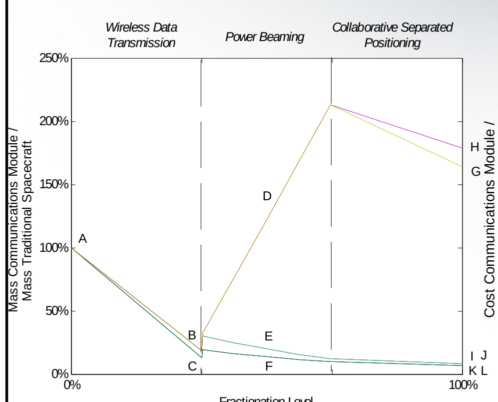
Notional

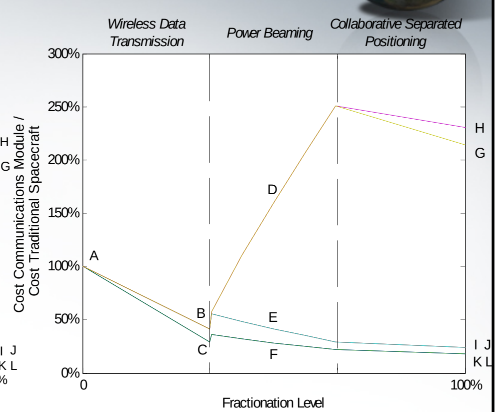


M_{module} Mass of the exchanged module
$M_{trad\ S/C}$ Mass of the traditional spacecraft

C_{module} Cost of the exchanged module
$C_{trad\ S/C}$ Cost of the traditional spacecraft

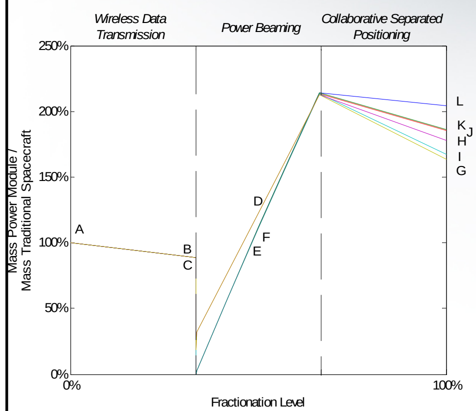
Architectures Maintainability in case of Communications Subsystem Failure

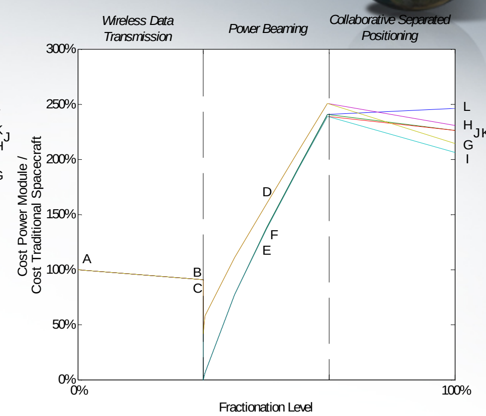




⇨ *Major Influence of the Power Subsystem*

Architectures Maintainability in case of Power Subsystem Failure





⇨ *The largest power modules are not always the ones containing other subsystems*

Two Other Opposite Effects of the Fractionation on the System Mass

If the Power Module is Fractionated in its own Module

<u>Mass tends to be lower</u>
than if fractionated in a module containing other subsystems

−

The power module only contains the power subsystem

<u>Mass tends to be larger</u>
than if fractionated in a module containing other subsystems

+

Additional power is needed to be beamed to the other modules

Conclusions

- ⇨ Major Influence of the Power Subsystem
- ⇨ Complexity of the Opposite Effects of Fractionation
- ⇨ Promising results for the fractionated spacecraft despite not very favorable models
- ⇨ If non-traditional attributes are valued enough, customers would choose fractionated spacecraft over traditional ones

Future Research

- ⇨ Improved “Flexibility” Metrics Using Real Options
- ⇨ Analysis of an Infrastructure of Fractionated Spacecraft
- ⇨ Analysis of the New Paradigm and of the Policy Options to Enable the Paradigm Shift

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ASSESSING THE FLEXIBILITY PROVIDED BY AN ON-ORBIT INFRASTRUCTURE OF FRACTIONATED SPACECRAFT

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ABSTRACT

This paper introduces the concept of an on-orbit infrastructure of fractionated spacecraft. Spacecraft fractionation transforms the traditional monolithic spacecraft into a set of free-flying modules, where infrastructure modules provide a payload module with power, communications, etc. Once launched, the supporting modules could be reused for other missions, and if standardized, they could form a whole on-orbit infrastructure that could support different payloads. Models were developed to assess various architectures of fractionated spacecraft supported by such an infrastructure using multi-attribute analysis. This evaluation is done from a customer-centric perspective in terms of traditional attributes such as mass and cost, but also of non-traditional attributes such as maintainability, flexibility, and scalability. The latter are likely to be valued given the uncertainty associated with the system, and real options form an appropriate framework to evaluate them. In fact, maintainability embodies the option to limit potential downsides, whereas scalability and flexibility represent options to take advantage of potential upsides. This study demonstrates that if these non-traditional attributes are valued enough, customers would choose fractionated spacecraft over traditional ones.

I. INTRODUCTION

Spacecraft are traditionally designed for a specific mission. Therefore, they tend to be monolithic and have a customized bus. Such an approach leads to high costs and risks associated with each mission and prevents reuse, especially of launched elements. The concept of spacecraft fractionation changes this paradigm, as it transforms the traditional spacecraft into a network of elements, where a free-flying payload module is supported by nearby free-flying modules that supply the functions usually provided by the spacecraft bus. Spacecraft fractionation was presented as a way to decrease the risks associated with launch [1], and in a first paper [2], fractionated spacecraft were demonstrated as providing customers with more flexibility, scalability, maintainability, and responsiveness than equivalent traditional spacecraft. But to fully appreciate the potential benefits of this concept, the analysis must go further.

Spacecraft fractionation makes a clear distinction between the value-added payload and its supporting functions. The supporting modules could actually be standardized and reused for different missions. One could then imagine building a whole on-orbit infrastructure that could support various payloads. Thus, today's bus platforms would no longer be designed and launched for a one-time use but would become a reusable infrastructure. This second paper investigates the impact of fractionation on a spacecraft, which is now part of a larger infrastructure.

II. SPACECRAFT FRACTIONATION

The type of fractionation investigated in this study breaks down a spacecraft into its functional elements. This concept is now conceivable thanks to the technologies being developed for distributed space systems. The payload and its supporting subsystems are implemented in different free-flying modules, which all form a single system.

The fractionated spacecraft is presented along with the traditional spacecraft on Fig. 1. In today's traditional approach, a spacecraft is built around a payload (yellow block), which is supported by various subsystems such as the power, communications, or propulsion subsystems (white blocks).

An equivalent fractionated spacecraft consists of the same components but physically separated into a payload module and one or several infrastructure modules. The payload module contains a payload identical to the one in the traditional spacecraft (yellow block) and the supporting functions that are not fractionated (orange block). The infrastructure modules consist of the same supporting functions as in the traditional spacecraft (white blocks) and additional hardware (blue blocks).

III. CONCEPT ASSESSMENT METHOD

1. Multi-attribute Trade-Space Exploration

The concept of an infrastructure of fractionated spacecraft is investigated using Multi-attribute Trade-Space Exploration. This method takes a customer-centric approach as it assesses architectures in terms of the attributes valued by possible customers. The attributes taken into account can include traditional ones, such as performance, as well as non-traditional ones, such as flexibility, and each of them are evaluated independently from the others. The architectures examined are described by a set of design parameters, and form the design vector. By varying the values of the design parameters, a trade-space of architectures is defined. The

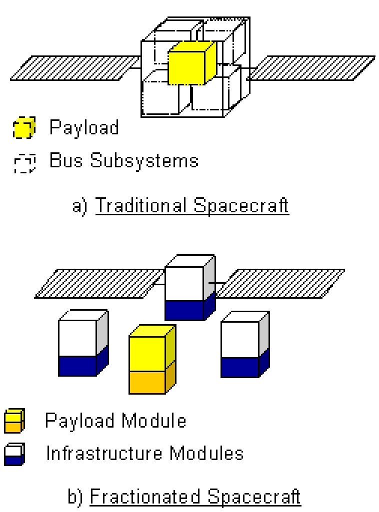


Fig. 1: Traditional and Fractionated Spacecraft

exploration of this trade-space allows the assessment of these different architectures and analysis of sensitivity to the design parameters.

2. Attributes

The attributes chosen as evaluation criteria for this analysis are meant to reflect the value derived from space assets by any potential customer, allow a fair comparison of traditional and fractionated spacecraft in the same trade-space, and significantly vary between the traditional and fractionated spacecraft but also between the various fractionated spacecraft architectures. Thus, the systems are examined for a same lifetime but also at a same level of performance, which simply means that the spacecraft compared have a same payload. Therefore, what is measured is the variation in value delivered to the customer by these systems at a given performance level.

The attributes assessed in this study are: mass, maintainability, scalability, and flexibility. While mass is a typical attributes of concern to customers of spacecraft systems, the latter three represent non-traditional attributes likely to be valued in a dynamic, uncertain environment. In addition, cost is taken into account as an independent variable.

As detailed in [2], maintainability is defined as an active response to an internal failure, scalability as an active response to a need for an increased performance level, and flexibility as an active response to a need for a new function.

IV. FRACTIONATED SPACECRAFT ARCHITECTURES

1. Fractionation of a Single Spacecraft

Design Parameters Associated with the Fractionation of a Single Spacecraft

If the fractionation of a single spacecraft is considered, the design parameters describing the architectures examined are:

- The subsystems fractionation level
- The technologies taken into account
- The number of infrastructure modules
- The subsystems contained in these modules

In a fractionated architecture, the supporting functions provided by the traditional spacecraft bus are distributed between the payload module and the infrastructure modules. A level of fractionation, from 0 to 100%, can then be defined for each subsystem, representing the distribution of this function between the module dedicated to that function and the rest of the modules. The subsystems considered as potentially "fractionable" in this study are the communications, control and data handling, power, attitude determination and control, and propulsion subsystems.

A fractionation level can also be defined at the spacecraft level, and can characterize the degree of fractionation of the spacecraft architectures relative to each other. This spacecraft fractionation level has two main dimensions. The first is the supporting function distribution between the payload and the infrastructure, and the second is the number of separate infrastructure modules.

First as some subsystems are more easily "fractionable", various sequences of subsystem fractionation that evolve a traditional spacecraft to a totally fractionated spacecraft can be defined. The one chosen in this study is based on today's technology maturity level and is presented in Fig. 2. The focus is not on a particular technology but more on a capability that could be reasonably implemented using different technologies. The 0% fractionation level corresponds to the traditional monolithic spacecraft. In the first step of the fractionation process, the possibility of wireless data transmission is considered, which leads to the complete fractionation of both the communications and the control and data handling subsystems. For the purposes of this study, the fractionation level of these two subsystems modules is either 0 or 100%. In the second step, the possibility of beaming power is considered, but this time the fractionation can be partial, on a continuum from 0 to 100% of fractionation, and two different approaches are taken into account: either both the power generation and storage function are fractionated at the same time, or the power generation is entirely fractionated in the power module and only the storage is distributed between the power module and the other modules. Finally, the possibility of collaborative separated positioning is considered, which would lead to the complete fractionation of both the attitude determination and control and the propulsion subsystems.

The second dimension of fractionation at spacecraft level concerns the number of separate modules that form the infrastructure architecture. As the infrastructure can consist of more or fewer modules, this number gives another measure of the spacecraft fractionation level.

Architectures Matrix

A matrix of the possible architectures was built using the two fractionation dimensions as shown on Fig. 3. Each box represents a module, and each architecture is labeled with a circled letter from A to G. The architectures can be ranked from the least to the most fractionated, i.e. from architecture A to architecture L. Fractionation strategies can be defined as the different paths along the technology axis, from the traditional spacecraft architecture to one of the most fractionated architectures, i.e. architectures G through L. As mentioned above, only architectures D, E, and F correspond to a continuum along the fractionation paths and are represented by plain lines, whereas the other architectures are represented by dots artificially linked with dotted lines.

2. An Infrastructure of Fractionated Spacecraft

Additional Design Parameters at Infrastructure Level

In this paper, the spacecraft investigated are assumed to be now part of a larger infrastructure. There are thus new parameters to take into account in the evaluation. First, the development of a whole infrastructure requires the standardization of the modules, which means a single or a limited number of modules design to support different payloads. At spacecraft level, this suboptimality implies that the modules may be oversized for its payload. A standardization parameter, *s*, simply defined as the percentage of additional payload mass and power requirements the modules could support, is therefore added to describe the architectures investigated. This parameter has an impact on both the spacecraft mass and costs. In addition, the production of standardized modules has other two major consequences on spacecraft costs: learning

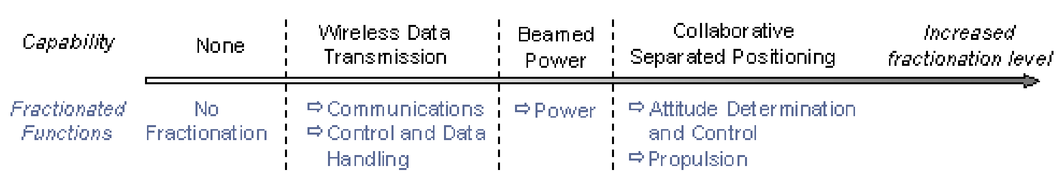
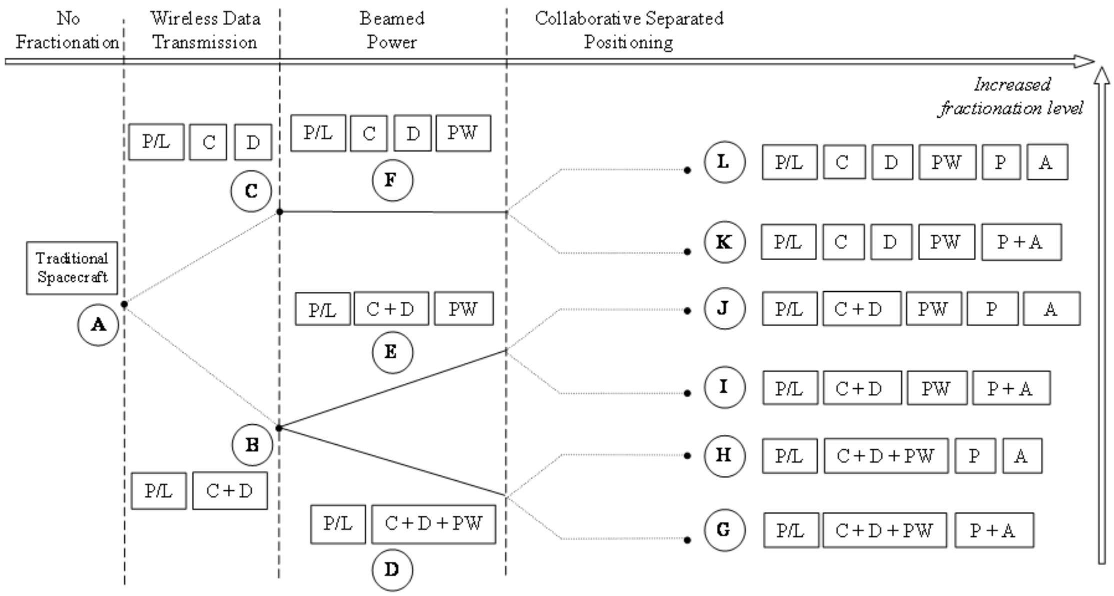


Figure 2: Fractionation Technology Axis



Modules — *P/L Payload*, *C Communications*, *D Control and Data Handling*, *PW Power*, *P Propulsion*, *A Attitude Determination and Control*

Fig. 3: Architectures Definition Matrix

effects are expected both in manufacturing and in integration, assembly, and test, and the initial development costs can be divided among all the identical modules. These two effects only depend on the number of units produced, which can reasonably be assumed to be the same for all types of modules. So the number of sets of modules is used as an additional design parameter of the architectures examined. No learning effects on launch are taken into account, and a single learning factor is used for all types of modules.

V. ATTRIBUTES ASSESSMENT MODELS

1. Mass Model

In the mass model, the spacecraft is described by its payload, which is defined by mass and power requirements, and its architecture. Given a payload, the first step of the model is to size the corresponding traditional spacecraft. The supporting subsystems are sized using mass ratios and power ratios. Different mass ratios are used depending on the mission application. Three main types of missions are investigated: communications, sensing, and navigation.

In the model, when a subsystem is fractionated, it is taken out of the spacecraft as it is and becomes the "payload" of a new module. For instance, when the communications subsystem is fractionated, it becomes a communications module with its own power, propulsion, attitude control, and thermal subsystems. The mass ratios are used to size the subsystems of this new module and the power ratios are used to size the power required by these subsystems, given the initial power requirement of the subsystem. Moreover, fractionated modules and the platform bus of the payload module are oversized according to the standardization parameter.

Additional masses and power due to wireless data transmission, power beaming, or collaborative separated positioning are added. For instance, the power module has additional mass and power to beam power to all the other modules and compensate for the losses. They have been modeled as percentages of the masses or powers of the sizing subsystems. For instance, the mass of the wireless data exchange subsystem of the communications module is defined as a percentage of the mass of the communications subsystem. Various technologies have been examined and sensitivity analyses have been run on these parameters.

The mass of the various fractionated architectures relative to an equivalent traditional architecture are evaluated for different standardization parameters and number of identical units produced.

Because of the mass model structure, the mass penalty, defined as a percentage of an equivalent traditional spacecraft mass, is independent from the payload mass and power.

2. Cost Model

The cost model is built using cost estimating relationships based on subsystem masses [3]. For comparability purpose, a traditional spacecraft cost model is used for both the traditional and the fractionated spacecraft.

The model computes the spacecraft total costs, which includes the development, manufacturing, integration, assembly, and test, and launch costs.

As the fractionated spacecraft are part of an infrastructure, various effects are taken into account in the costs of their recurring elements, i.e. the supporting modules and the platform of the payload module. First, the opposite impacts of standardization and learning are considered in the manufacturing and integration, assembly, and test costs. A unique learning factor of 0.85, which is typical value in aerospace industry [4], is used. In addition, the development costs are divided among spacecraft with identical modules, so only a percentage of the initial development effort is assigned to each spacecraft.

The average unit cost of the various fractionated architectures relative to an equivalent traditional architecture are evaluated for different standardization parameters and number of units produced.

3. Non-traditional Attributes Evaluation

The non-traditional attributes taken into account correspond to options provided to the customers so that they can better manage the main uncertainties associated with the system. Maintainability embodies the option to limit potential downsides, whereas scalability and flexibility represent options to take advantage of potential upsides. All of them are measured in monetary units, and for each of them, a scenario is defined.

Maintainability

To assess architectures maintainability, one of the supporting subsystems is assumed to fail and lead to the spacecraft complete failure. For fractionated architectures, the module containing the corresponding subsystem is assumed to be exchanged with an identical one. For the traditional architecture, the whole spacecraft is assumed to be exchanged. The manufacturing and launch costs of a new identical module relative to the cost of a new traditional spacecraft are used as a maintainability metric.

Fractionated spacecraft may not be initially less expensive than traditional spacecraft, but are bound to be cheaper to maintain. To get a better sense of the value of the maintainability provided by the fractionated spacecraft, the initial and maintenance costs of the fractionated architectures are used to perform net present value (NPV) calculations for various scenarios of failure, as done for instance in [5]. This part of the model is currently limited to communications satellite as the revenues they generate is simple to define in monetary units, as a function of the number of transponders. For a given supporting function, a failure profile is defined with a constant failure rate most of the lifetime and an infant mortality and a wear-out periods at the beginning and at the end of the lifetime. In case of failure, the decision-maker is assumed to choose to exchange the failing module if the revenues over the rest of the spacecraft lifetime are expected to be larger than the maintenance "costs". The risks associated with such an exchange are not taken into account, but in case of maintenance, only part of the yearly revenue is assumed to be generated. Depending on whether and when the failure occurs, the net present value differs. Given a failure profile, a net present value distribution is obtained for each architecture.

Scalability

To assess architectures scalability, an increased level of performance is assumed to be needed. The additional performance needed is described by a single parameter *p*, which is defined as a percentage of the initial mass and power requirements of the payload. For fractionated architectures, a new payload module is assumed to be added to the existing one. The new payload module consists of: a payload sized by the increase of performance needed; the corresponding supporting functions that are not fractionable; and depending on the value of the increase of performance needed and the standardization parameter, it may also include fractionated supporting functions. Because of standardization, fractionated spacecraft may have oversized supporting functions. Therefore, if additional performance is needed from the supporting functions, these margins may in some cases be sufficient. If they are, the new payload module contains only the payload and the supporting functions not fractionable, both sized by the increase in performance needed. But if they are not, then additional functions are added to the new payload module to provide the difference between the performance level already supplied by the infrastructure functions and what is needed.

For the traditional architecture, the whole spacecraft is assumed to be exchanged with a new one with the level of performance needed. Both the new payload module and its equivalent traditional spacecraft require a limited new development effort. The development, manufacturing, and launch costs of the new payload module relative to the costs an equivalent traditional spacecraft are used as a scalability metric.

The initial and upgrade costs of the fractionated architectures are used to perform net present values calculations for different demand scenarios. A simple scenario assumes that at some point in time, the performance level, which after a ramp-up period is assumed constant, changes to a new constant value for the rest of the spacecraft lifetime. To the initial and new performance values are associated different yearly revenues. If the demand increases, the decision-maker may choose to upgrade the spacecraft if the expected revenues over the rest of the spacecraft lifetime are higher than the upgrade costs. As the new level of revenue potentially generated by the spacecraft can equally be lower or higher than the initial one, a normal distribution centered on the initial value with a volatility increasing with time is used. Depending on when this change occurs and the new revenues that can be potentially generated, different net present values are obtained. Thousands of net present value computations are run to get the net present value distribution for each architecture. These distributions are then compared.

Flexibility

To assess architectures flexibility, a new function is assumed to be needed. To distinguish this scenario from the scalability one, the payload corresponding to this new function is assumed to have similar requirements in terms of mass and power as the initial one, so that the initial infrastructure modules can be reused as such. For fractionated architectures, the payload module is exchanged with a new one that includes the newly-developed payload. For the traditional architecture, the spacecraft is exchanged with a whole newly-developed one. The payload module new development, manufacturing, and launch costs relative to the same costs for a whole traditional spacecraft are used as a flexibility metric.

The initial and exchange costs of the fractionated architectures are used to perform net present values calculations for different demand scenarios. A simple type of scenario assumes a constant yearly revenue flow for the initial spacecraft and that at some point in time, a new function potentially generates larger revenues but also simultaneously make the revenues generated by the initial function decrease to a lower level. If the difference in expected revenues is larger than the exchange costs then the decision-maker will choose to exchange the payload module. The level of revenue of the new function was assumed to be independent of the new level of revenue of the original function. As it was assumed that the new payload has the same requirements as the initial one, the difference between the potential revenues generated by the new function and the ones initially generated by the original function has to be within a reasonable range. To each possible scenario is associated a net present value. All new levels of revenues were assumed to be equally probable within given ranges. Thousands of net present value computations are run to get the net present value distribution for each architecture. These distributions are then compared.

VI. ASSESSMENT RESULTS

A communication mission was chosen to illustrate the results of this model. But as mentioned earlier, at least part of the same analysis can be performed for sensing and navigation missions. Moreover, the power fractionation strategy in which both the power generation and storage functions are fractionated simultaneously is the one assumed. Finally, as a scale for the infrastructure has to be chosen, one hundred fractionated spacecraft with similar designs are assumed to be produced.

1. Impact of the Fractionation on the Spacecraft Total Mass

An expected drawback of spacecraft fractionation is mass penalty. Figure 4 presents the mass penalty as a percentage of the equivalent traditional spacecraft mass for the different architectures, labeled from A to L, and for two different values of the standardization parameter s. In the first case, s = 0%, the spacecraft has correspond to the maximum payload mass and power requirements that the infrastructure modules can support, so that the design of the modules is optimal. In the second case, s = 30%, the payload of the spacecraft is 30% lighter and requires 30% less power than the infrastructure modules can support.

Using traditional mass models, the mass penalty is expected to vary in the first case between 5 and 200% from architecture B to architecture L, and in the second case between 30% and 275%. This penalty clearly increases with fractionation, except for architectures G, H, and I. As explained in [2], this phenomenon is due to two opposite effects of fractionation on the total system mass. When a function is fractionated, the number of modules and interfaces increases, which makes the mass increase. But at the same time, as the function is no longer needed in the other modules and gets centralized, mass tends decrease. The relative magnitudes of these two effects finally decides whether mass will increase or not with the fractionation of a function

Figure 4 illustrates the major role played by the power function. The fractionation of the power function is obviously responsible for most of the total mass penalty of the fully fractionated architectures (G to L). As already underlined in [2], the main emphasis has to be put on power technologies to make the fractionated spacecraft concept viable.

The standardization parameter s has clearly an impact on the mass penalty associated with each architecture. For instance, the architecture L is associated with a mass penalty of 200% for s = 0%, and 275% for s = 30%. One can notice that, in this example, when s increases from 0% to 30%, the mass penalty increases by more than 30%. Moreover, the standardization parameter has also an impact on the difference of mass penalties between the various architectures. For instance, the difference in mass penalty between the architectures G and L is larger for s = 30% than for s =0%.

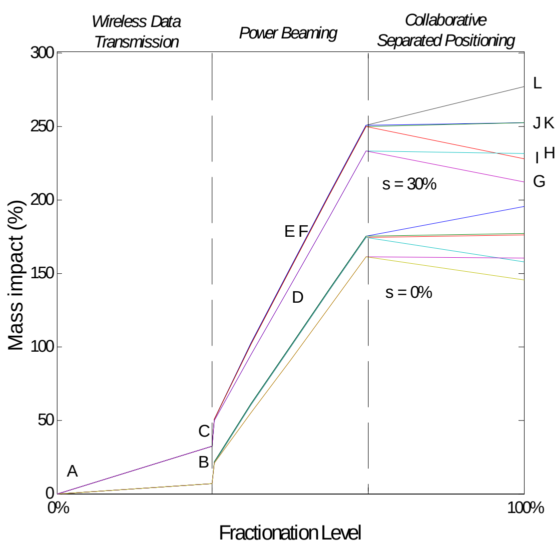


Fig. 4: Mass Penalty due to Fractionation for Different Standardization Parameter (s)

2. Impact of the Fractionation on the Spacecraft Cost

As presented above, fractionated spacecraft are expected to be heavier than equivalent traditional ones, and this mass penalty increases with the standardization parameter. On the one hand, a cost penalty is associated with this mass penalty. On the other hand, learning effects and development costs sharing tend to decrease the fractionated spacecraft costs relative to traditional spacecraft costs. These opposite effects determine the total costs of the fractionated architectures relative to the traditional ones. It is noteworthy that the learning effects and development costs sharing reduce both the development and manufacturing costs but not the launch costs, which remain directly proportional to the mass, as no learning effects are taken into account for launches. This also means that cost figures can be considered as an upper bound as one could expect at least some learning effects on launch costs if the infrastructure is developed.

Figure 5 presents the total cost impact as a percentage of an equivalent traditional spacecraft cost for all the fractionated architectures for two different values of the standardization parameter.

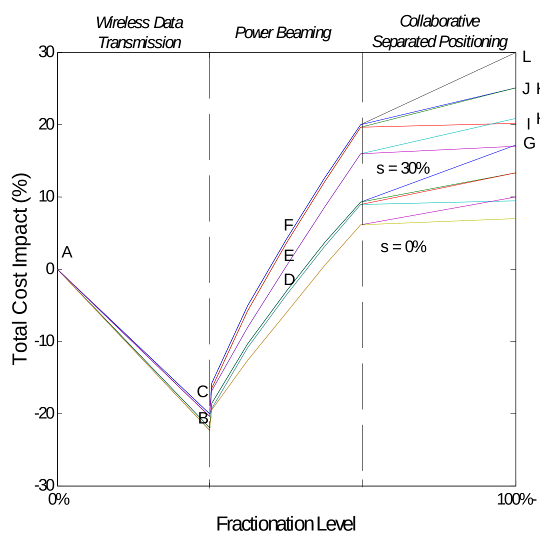


Fig. 5: Cost Penalty due to Fractionation for Different Standardization Parameter (s)

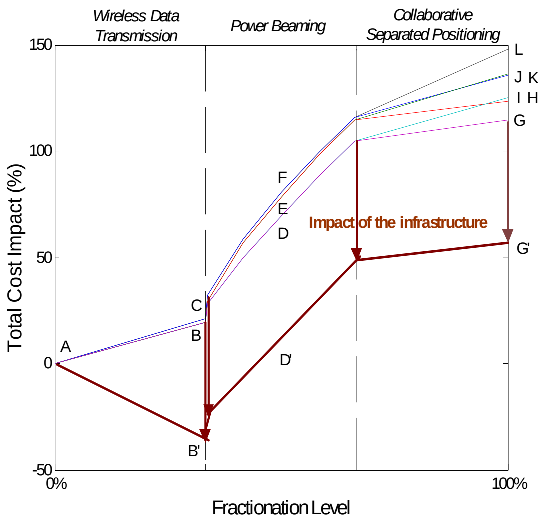


Fig. 6: Impact of the Infrastructure on the Cost Penalty for *s* = 30%

In this example, the cost impact varies between -20% and +17% for a standardization parameter of 0%, and between -20% and +30% for a standardization parameter of 30%.

The cost decrease from the traditional architecture A to the fractionated architectures B and C can seem counterintuitive given the results presented on Fig. 4. The cost penalty that corresponds to the mass penalty presented on Fig. 4 for *s* = 30% is presented on Fig. 6. But this cost penalty does not take into account any learning effect or development cost sharing. These two effects actually translate down the costs of the fractionated architectures, while the cost of the traditional spacecraft A remains constant. This impact on the fractionated architectures' costs is represented by the arrows on Fig. 6. For instance, architecture B becomes B', the set of architectures D become D', and architecture G becomes G'. Depending on the amplitude of these effects, the fractionated architectures can then become cheaper than the traditional architecture.

Like for mass, the standardization parameter has an impact on both the cost penalty associated with each architecture and the difference of cost penalties between architectures. For instance, the architecture L goes from a cost penalty of 17% for *s* = 0% to a penalty of 30% for *s* = 30%, and this increase in cost penalty is much larger than the increase of 30% of the standardization parameter. In addition, the difference in cost penalties between the architectures G and L increases by more than 30% when s goes from 0% to 30%.

Architectures B and C have the lowest initial costs among the fractionated architectures and are even cheaper than the traditional architectures. Then as fractionation increases, the fractionated architectures become more expensive, and more expensive than the traditional one. Again, the power is responsible for most of the cost penalty of the fully fractionated architectures.

3. Impact of the Fractionation on the Spacecraft Non-traditional Attributes

Maintainability

Two examples of supporting function failure are presented to illustrate the maintainability metric. A standardization parameter of 30% is assumed.

First, a failure of the communication subsystem is assumed. Figure 7 presents the maintenance cost for the different fractionated architectures as a percentage of the exchange cost for an equivalent traditional spacecraft. The maintenance cost is for all fractionated architectures significantly lower than the cost of a traditional spacecraft exchange, even for the architectures D, G, and H. In these architectures, the power subsystem is fractionated in the same module as the communications subsystem, and in fact this module becomes larger than the initial traditional spacecraft [2]. But the learning effects applied to the infrastructure modules manufacturing more than compensate the cost penalty linked to the size of the module.

The second example investigates the particular case of the power module. A total failure of the

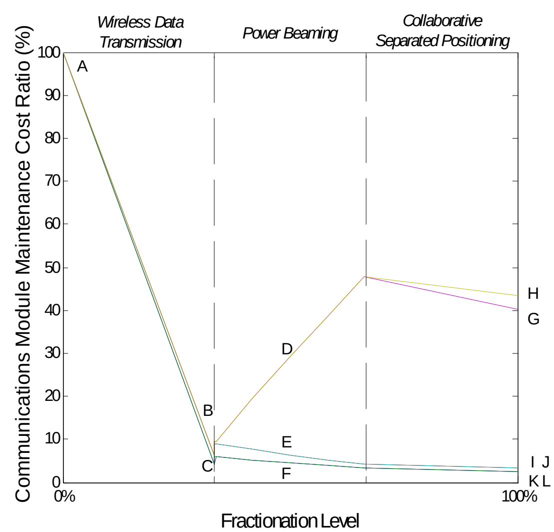


Fig. 7: Cost of the Communications Module Upgrade Relative to the Traditional Spacecraft Cost

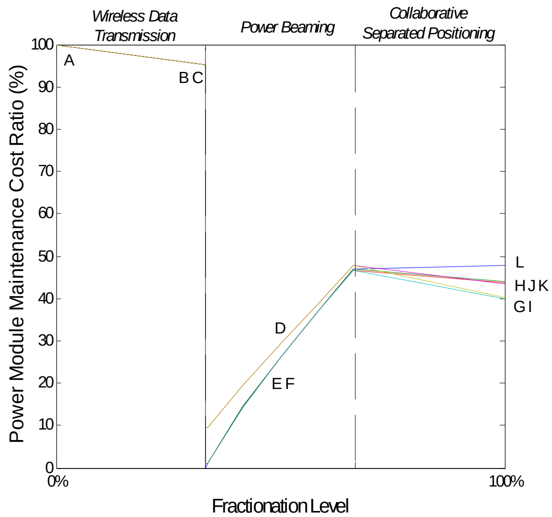


Fig. 8: Cost of the Power Module Upgrade Relative to the Traditional Spacecraft Cost

power subsystem is assumed. Figure 8 presents the relative maintenance cost for all the fractionated architectures. On the left third of the figure, the module that contains the power subsystem is the payload module. Then, as the fractionation level increases, the power fractionated is either, like in architecture D, added to the communications and data handling module, or a new power module is created, like in architectures E and F. This difference explains the step when the power starts getting fractionated in the case of architecture D. For architectures D to L, the cost to maintain the power subsystem is much lower than the cost of a traditional spacecraft. Again, the learning effects compensate the mass of the module, which becomes larger than the initial traditional spacecraft.

Figures 7 and 8 clearly demonstrate and quantify the much better maintainability of all the fractionated architectures relative to the traditional one. As could be expected, architectures B and C are the "most maintainable" in case of communications subsystem failure, whereas all the other fractionated architectures are "more maintainable" than these in case of power subsystem failure, which demonstrates a trade-off to be made when choosing an architecture, depending on subsystems reliability.

If, for a given subsystem, these cost results are associated with an expected revenue flow and a set of failure scenarios, the resulting distribution of net present values for the different architectures can be drawn. The failure of the power subsystem, which is one the most frequent ones, is used as example. For a 90% reliability of the power subsystem over the spacecraft lifetime, the net present value of the spacecraft has 90% chance to reach its maximum value. This maximum value depends on the expected value of the revenue flow and the initial costs. Therefore, as can be concluded from Fig. 5, the architectures B and C will have the largest maximum net present value, followed by the traditional spacecraft, and then the other fractionated architectures. But one should also look at what happens in the 10% chance that corresponds to the risk of failure. In case of failure of the power subsystem, the traditional spacecraft is unlikely to be exchanged. As a result, the revenues generated by the spacecraft definitely drop to zero. But as fractionated spacecraft can be maintained at much lower costs, they may be maintained, which enable customers to go on deriving revenues from the spacecraft. Therefore the net present value decreases in the 10% chance of failure much less for the fractionated architectures than for the traditional one as illustrated on the notional curves of Fig. 9. On this figure, the plain line represents a notional cumulative probability distribution of the net present value for the traditional architecture, the dashed line, one for the architecture B, and the dotted line, one for the architecture G. This difference shows how the fractionated spacecraft enable to capture revenues that otherwise would be lost, and can be measured using the concept of value at risk. The value at risk (VAR), introduced in [6], is the minimum value one can gain or maximum value one can loose at a given level of confidence. In fact, the minimum value at risk for a given level of confidence tend to be larger for all the fractionated architectures than for the traditional spacecraft. Fig. 9 shows that even though the traditional architecture may have a larger net present value than some of the fractionated architectures, its value at risk, here for a 95% level of confidence, tend to be lower than the all the ones of the fractionated architectures. The first conclusion is that architectures B and C completely dominate the traditional architecture as they both have a larger net present value and a larger value at risk for a high level of confidence. The architectures D to L, which are initially little more expensive, have a lower maximum net present value than the traditional spacecraft but a much larger value at risk at a high level of confidence. These benefits provided by fractionation are directly proportional to the

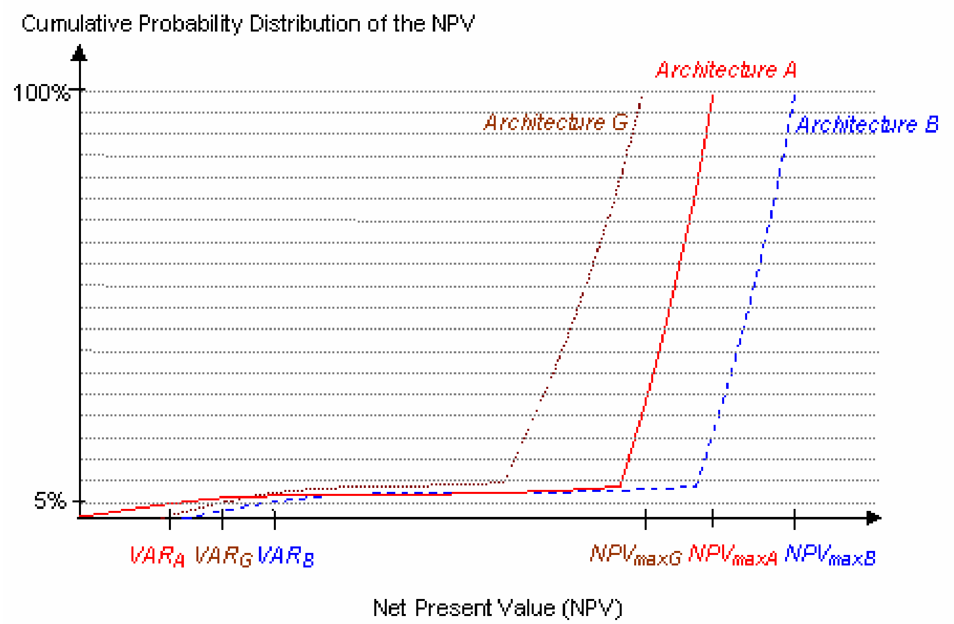


Fig. 9: Value at Risk for a 95% Confidence Level and Maximum Net Present Values for Different Architectures

reliability of the subsystem. An interesting trade-off can be made between reliability and maintainability for the fractionated spacecraft. A lower reliability would enable designers to reduce costs, and increase the maintainability of fractionated spacecraft relative to traditional ones, and this would increase their net present value and value at risk differences with traditional spacecraft.

Scalability

Scalability represents the ability of the system to response to the need for an increased level of performance. To illustrate the scalability provided by spacecraft fractionation, a spacecraft with a standardization parameter *s* of 30% is assumed, which means that the infrastructure supporting the payload can support, partly or entirely, an additional payload.

Figure 10 presents the upgrade cost relative to a traditional spacecraft exchange for different levels of performance increase needed. There is only one curve for each value of the percentage of performance increase *p*, as the architectures with a same fractionation level along the technology axis, i.e. B and C, D to F, and G to L, have similar payload modules, so their upgrade costs are the same.

Even when this increase is much larger than the margins provided by standardization, in this case 30% margins, the upgrade cost remains relatively low. One can notice that all fractionated architectures are almost as scalable as the others relative to the traditional spacecraft. When the standardization margins are larger than the performance increase needed, the payload module is the same for all architectures, which explains that the two lower curves are flat in the left two thirds of the figure. When the standardization margins are smaller than the performance increase, the payload modules are no longer the same, and the more fractionated the architecture, the more expensive they are, but

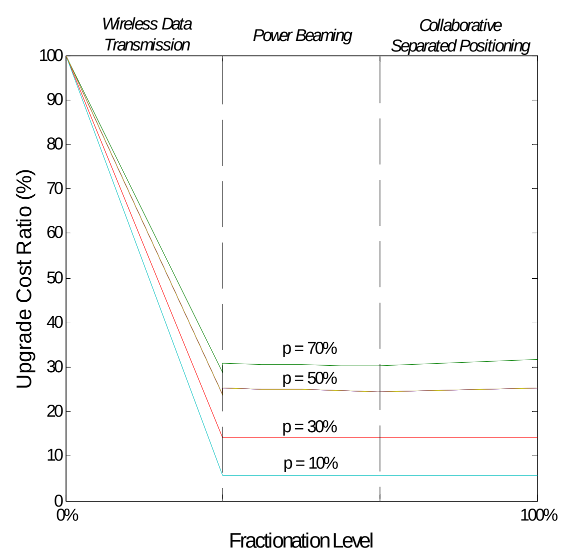


Fig. 10: Upgrade Cost Ratio for Various Percentages of Performance Increase (*p*)

their relative costs hardly varies.
It is important at this point to underline the difference between the three non-traditional attributes. The dominance of the fractionated architectures in terms of maintainability and flexibility is due both to the modularity of these architectures and the effects associated with the size of the infrastructure, i.e. learning effects and the development costs sharing. On the other hand, the dominance of the fractionated architectures in term of scalability is only due to the modularity provided by fractionation. It is simply due to the fact that only what is needed is developed, manufactured, and launched.
Figure 10 clearly demonstrates the superior scalability of the fractionated architectures, and that all the fractionated architectures are almost as scalable as the others. This figure also suggests that it may be worth investigating in more details strategies of staged deployment of fractionated spacecraft in cases of uncertain increase in the demand [7,8].
If these cost results are associated with a revenue flow and a set of demand, the distribution of net present values can be drawn for the different architectures. When compared, these distributions look like the notional curves presented on Fig. 11. The main difference between the traditional architecture, represented by the plain line, and the fractionated architectures is an increase the maximum net present value. When scalability is evaluated, fractionation mainly "stretches" the distribution towards larger values. This tendency reflects the fact that fractionated architectures enable customers to capture additional potential revenues that would otherwise be lost.

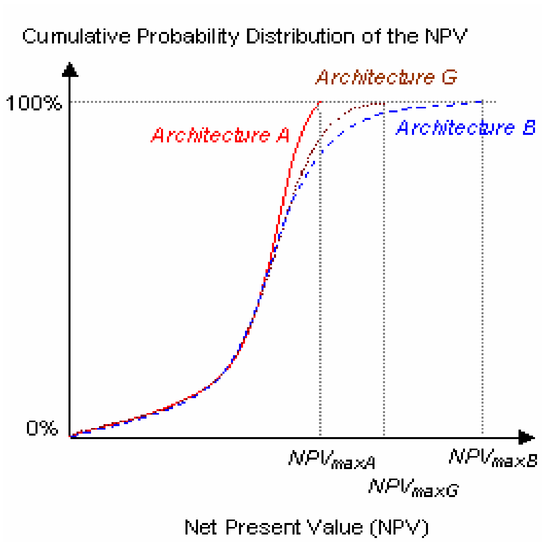


Fig. 11: Net Present Value Cumulative Probability Distribution for Different Architectures

Flexibility

Flexibility represents the ability of the system to respond to the need for a new function. In the flexibility scenario, the payload module of the initial spacecraft is assumed to be replaced with one that has a newly-developed payload but the same bus platform. Figure 12 presents the upgrade cost relative to an equivalent traditional spacecraft cost for different values of the standardization parameter. Like in the scalability assessment, there is only one curve for all the architectures for a given value of the standardization parameter. The exchange cost logically decreases as fractionation increases down to less than 50%. The more fractionated the architecture is, the less expensive the exchange is.
The advantage of the fractionated architectures in the flexibility examples lies in the learning effects and development costs sharing. Apart from launch costs, most of this exchange cost is the development and manufacturing costs of the new payload, which underlines how the concept of fractionated spacecraft enable customers to better use their funds by paying mainly for the new value-added payload.
If these flexibility cost results are associated with a revenue flow and a set of scenarios of demand, the corresponding distribution of net present values can be drawn for the different architectures. The same phenomenon as the one

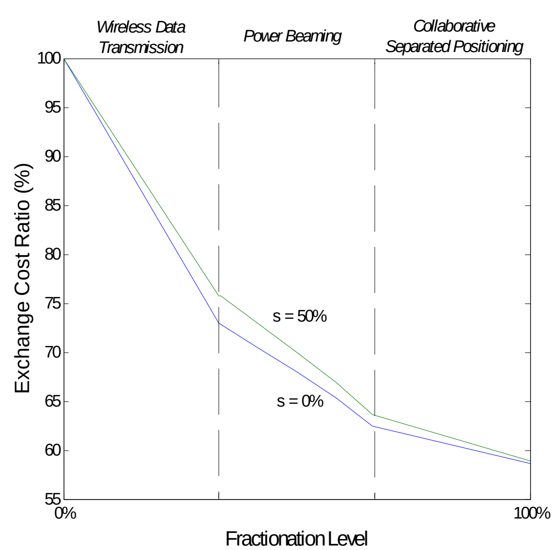


Fig. 12: Exchange Cost Ratio for Different Standardization Parameters (*s*)

described in the scalability assessment and illustrated on Fig. 10 is observed. Again, fractionation enables customers to capture new revenues, which increases the spacecraft maximum net present value.

VII. CONCLUSIONS

As illustrated in this study, fractionation at infrastructure level tend to increase both the maximum and the minimum expected value derived from space assets over their lifetime at limited costs, and even at lower costs in some cases. All the fractionated architectures investigated have their strengths and weaknesses in terms of traditional and non-traditional attributes, but they all have benefits over traditional architectures. And one should bear in mind that the traditional mass and cost models used are likely to be unfavorable to the fractionated architectures. In addition, for comparability purpose, the lifetime of the modules was set to the same lifetime as the traditional spacecraft, but one of the advantages of fractionation is that each module can have its own lifetime, shorter or longer than the one of the payload.

There are obviously risks associated with fractionation, but it has definitely many advantages and even possible synergies with other concepts, such as homogeneous fractionation or on-orbit servicing. Spacecraft fractionation revolutionizes the idea of space-based capability and spacecraft lifetime, creating a flexible, evolvable and scaleable system-of-systems infrastructure that would improve space utilization sustainability.

VIII. FUTURE RESEARCH

The development of such a modular infrastructure would have significant impact on all the aerospace industry players. As introduced in [2], fractionation creates a whole new paradigm in which today's prototype approach would become a mass production approach. Despite so many potential benefits, there are still major barriers to the shift from today's paradigm to the new fractionated spacecraft paradigm. The next phase of this work will explore potential policy options to enable such a transition.

ACKNOWLEDGMENTS

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IV. Accompanying presentation for paper presented at the International Astronautical Congress, October 2005, Japan

Assessing the Flexibility Provided by an On-Orbit Infrastructure of Fractionated Spacecraft

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Center for Aerospace Systems, Policy, and Architecture Research
Massachusetts Institute of Technology

Agenda

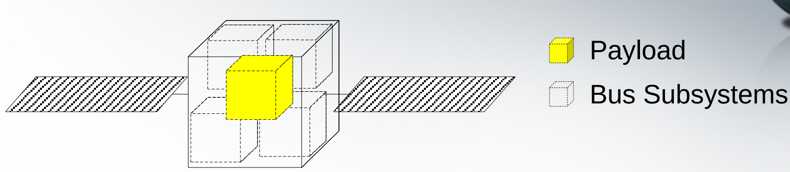
- Fractionated Spacecraft Definition
- Architectures Assessment Method
- Results of the Architectures Evaluation
- Conclusions and Future Research
- Questions

A Definition for the Fractionated Spacecraft

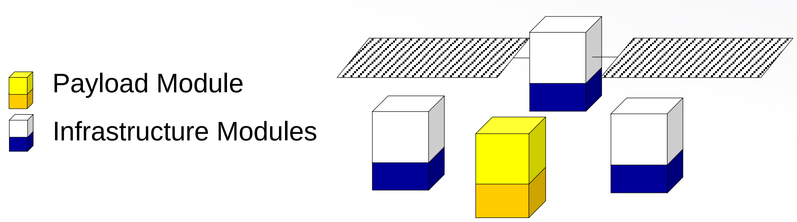
- Transforms the traditional monolithic spacecraft into a network of elements

- A free-flying payload module is supported by an on-orbit infrastructure composed of free-flying modules

From the Traditional Spacecraft



To the Fractionated Spacecraft



Multi-Attribute Trade-Space Exploration

1. Definition of the Attributes valued by Potential Customers
2. Definition of the Design Parameters
3. Definition of the Design Vector
4. Evaluation of the Architectures Attributes and Sensitivity Analyses

Architectures Assessment Criteria

Fractionated and traditional architectures are assessed at isoperformance and for a similar lifetime in terms of:

- *Traditional attribute*
  - Mass Impact
- Cost
- *Non-traditional attributes (or "ilities")*
  - Maintainability
  - Scalability
  - Flexibility

Definitions for the Non-Traditional Attributes

Maintainability

Active Response to an Internal Failure

Scalability

Active Response to a Need for an Increased Performance Level

Flexibility

Active Response to a Need for a New Function

Design Parameters at Spacecraft Level (I/II)

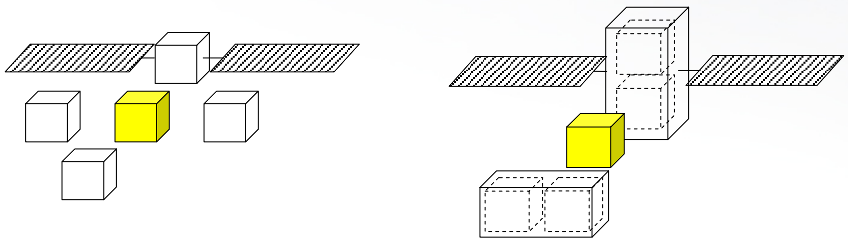
Fractionation Design Parameters

- Fractionated supporting functions
  - *Communications*
  - *Control and Data Handling*
  - *Power*
  - *Attitude Determination and Control*
  - *Propulsion*
- Power Function Fractionation Level
- Type of Power Fractionation

Design Parameters at Spacecraft Level (II/II)

Infrastructure Architecture Design Parameters

- Number of infrastructure modules
- Functions within each module



Spacecraft Fractionation Level

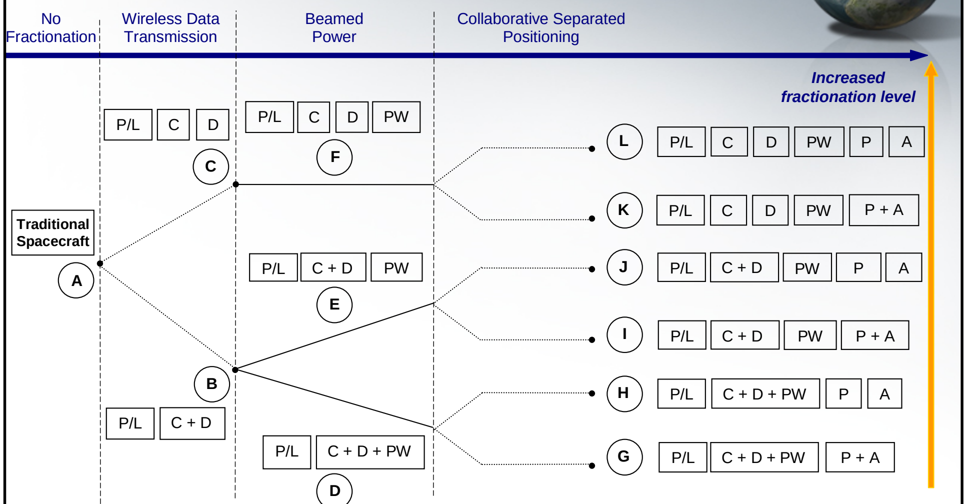
Two Main Fractionation Dimensions

- Technologies Considered and Functions Fractionated

Capability	None	Wireless Data Transmission	Beamed Power	Collaborative Separated Positioning	***Increased fractionation level***
Fractionated Functions	No Fractionation	⇨Communications ⇨Control and Data Handling	⇨Power	⇨Attitude Determination and Control ⇨Propulsion	

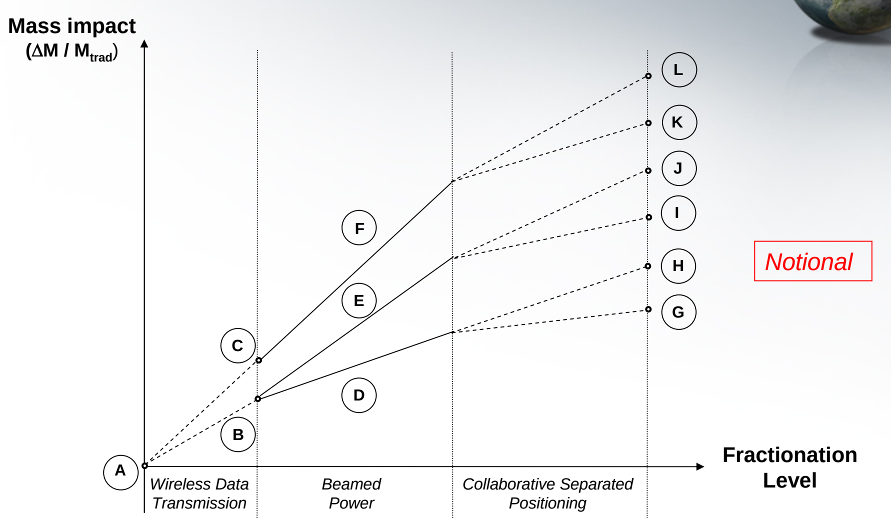
- Number of Infrastructure Modules

Fractionated Architectures Investigated



Modules: P/L Payload; C Communications; D Control and Data Handling; PW Power; P Propulsion; A Attitude Determination and Control

Fractionation Strategies and Mass Impact of the Fractionation



A < B < C < D < E< F < G < H < I < J < K < L

Additional Design Parameters at Infrastructure Level

- **Standardization Parameter *s***

  Because of standardization, the common infrastructure modules may be overdesigned for some of the payloads

  s = 30% represents a situation where common infrastructure modules are overdesigned for a particular payload by 30%, i.e. the infrastructure modules can support 30% more mass and power than is needed by the payload

  ⇒ *Impact on spacecraft mass and costs*

- **Number of Identical Infrastructure Modules Produced**
  - Learning effects reduce Manufacturing and IAT Costs
  - Development Costs Distribution

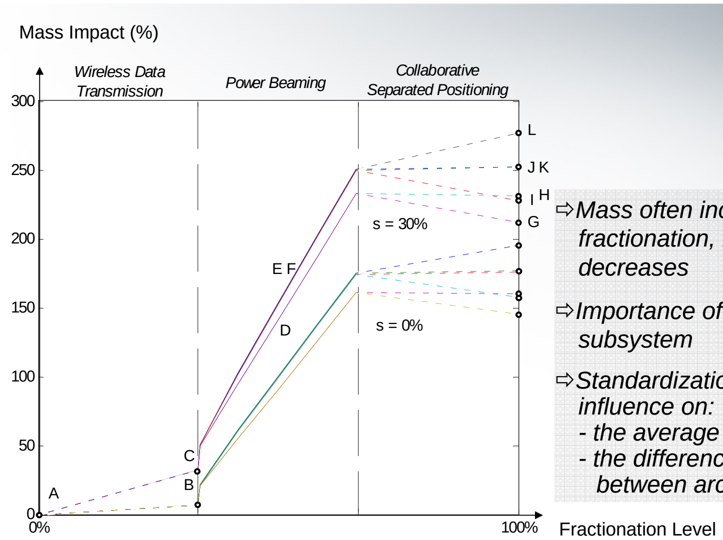
  ⇒ *Impact on spacecraft costs*

Example of Architectures Assessment

- Communication satellite
- Power storage and generation are simultaneously fractionated
- 100 identical sets of infrastructure modules produced
- Learning factor of 0.85

  Applied to manufacturing and iat costs but not to launch costs
- 2 possible values of the standardization parameter: *s* = 0% and 30%

Fractionation Mass Impact for Different Values of the Standardization Parameter *s*

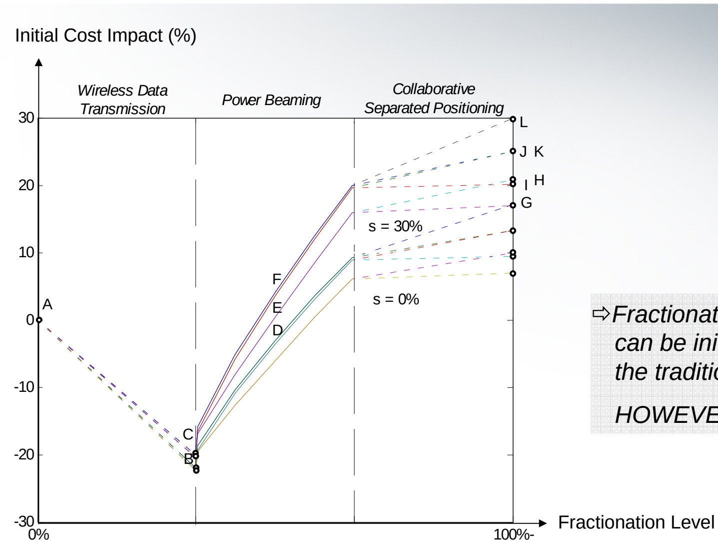


⇨ *Mass often increases with fractionation, but sometimes decreases*

⇨ *Importance of the power subsystem*

⇨ *Standardization has a significant influence on:*
- the average mass impact
- the difference of mass impacts between architectures

Fractionation Cost Impact for Different Values of the Standardization Parameter *s*



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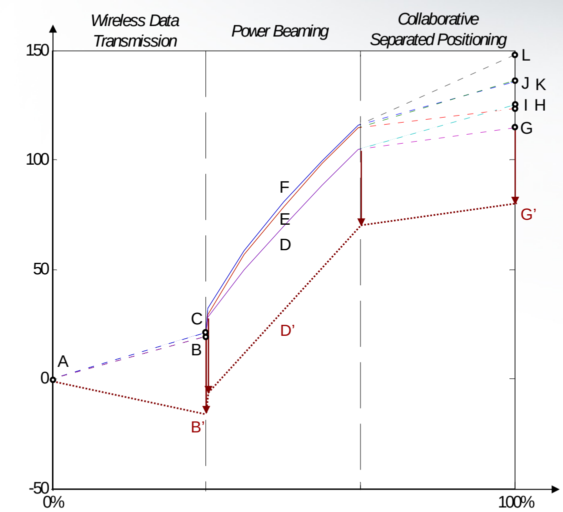
HOWEVER…

Impact of Learning Effects and Development Costs Sharing on Cost



s = 30%

These cost savings depend on two effects linked to the number of units produced:
- the learning effects
- the development cost sharing

⇨*Depending on the amplitude of these effects the costs of the fractionated architecture may be lower or higher than the cost of the traditional architecture*

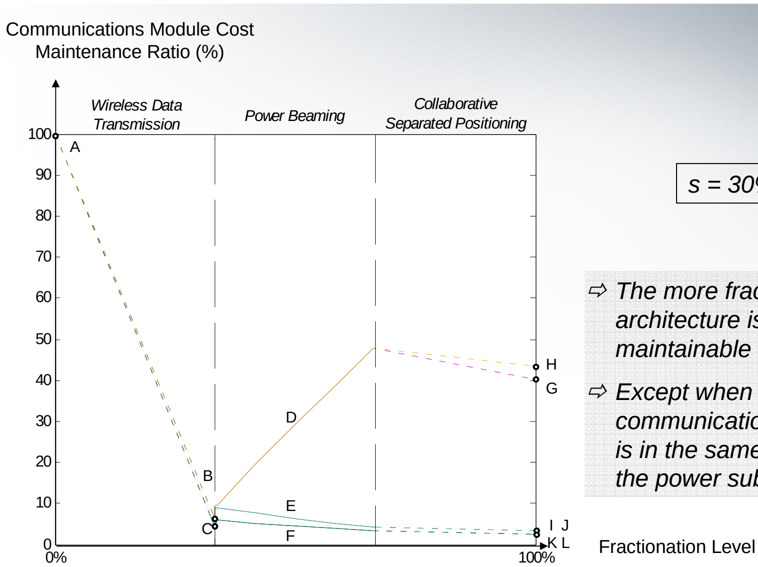
⇨*Fractionated architectures costs increases with fractionation*

⇨*Importance of the power subsystem*

Maintainability Assessment Scenario

- The failure of a supporting subsystem leads to a complete spacecraft failure
- For the fractionated architectures, only the module that contains the failing subsystem is assumed to be exchanged with an identical one
- The costs of manufacturing and launching a new module relative to the costs of the traditional spacecraft is used as a maintainability metric
- 2 examples of maintainability evaluation: failure of the communications and power subsystems

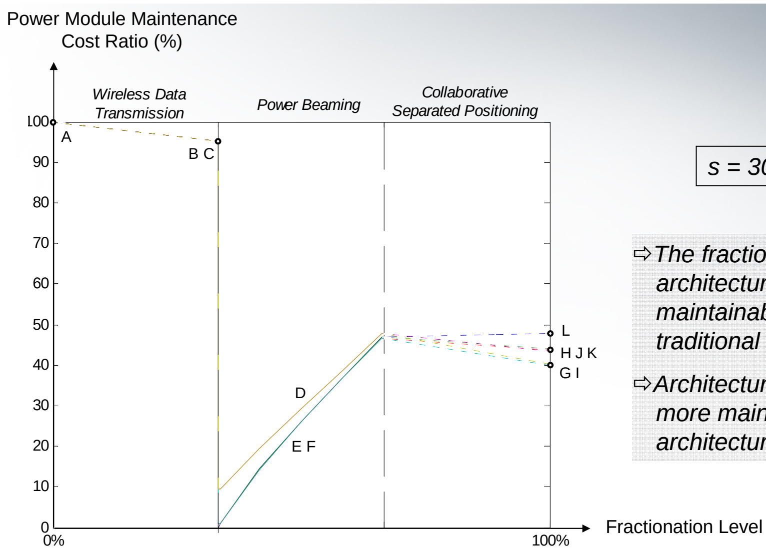
Architectures Maintainability in case of Communications Subsystem Failure



s = 30%

- The more fractionated the architecture is, the more maintainable it is
- Except when the communications subsystem is in the same module as the power subsystem

Architectures Maintainability in case of Power Subsystem Failure



s = 30%

- The fractionated architectures are more maintainable than the traditional one
- Architectures D to L are more maintainable than architectures B and C

Net Present Value Definition

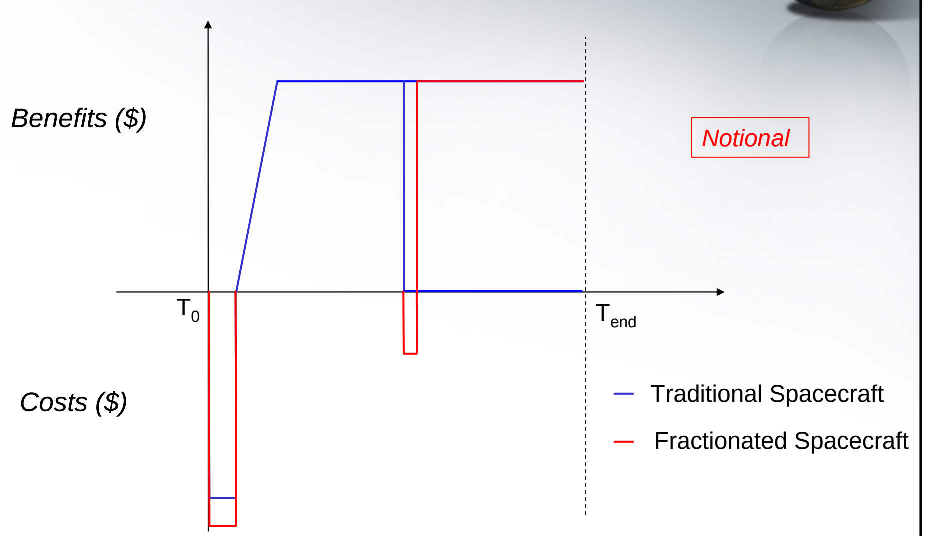
Each period t

The system will cost C_t and generate the benefits B_t
From the first period T_0 to the last one T_{end}

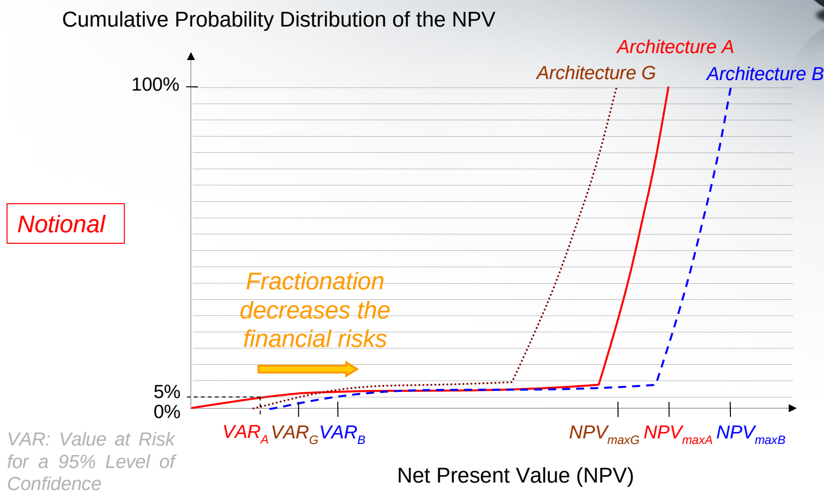
$$\text{Net Present Value} = \sum_{t=T_0}^{T_{end}} \frac{B_t}{(1+r)^t} - \sum_{t=T_0}^{T_{end}} \frac{C_t}{(1+r)^t}$$

T_0	First Period
T_{end}	Last Period
B_t	Benefits during period t
C_t	Costs during period t
r	Discount Rate

Revenues and Costs Profiles in the Maintainability Scenario



Net Present Values Distribution - Maintainability Scenario



⇨ *Fractionation enables customers to limit the potential downsides*

Maintainability Assessment

- Fractionated architectures are more maintainable than the traditional architecture
- Trade-off between reliability and maintainability
- Fractionation provides customers with options to limit potential downsides

Conclusions

- If non-traditional attributes are valued enough, customers would choose fractionated spacecraft over traditional ones
- All the fractionated architectures have their strengths and weaknesses and under certain assumptions dominate the traditional architecture
- Fractionation provides customers with options to limit potential downsides and derive benefits from potential upsides
- Fractionation provides customers with new trade-offs
- Models assumptions are conservative
- Immediate technology challenge is to reduce power subsystem mass

Future Research

- More analysis of the value of the options provided by spacecraft fractionation
- Investigation of the customer utility for the non-traditional attributes
- Analysis of a new paradigm to enable fractionated spacecraft and policy options to make it happen

V. Update briefing to Owen Brown (DARPA) and Paul Eremenko (BAH), December 2005, MIT

Fractionated Spacecraft Architecture Study

Charlotte Mathieu – Dr. Annalisa L. Weigel
CASPAR – MIT
December 5th 2005

Agenda

- Overview of the study and its results
- Utility interviews
- Brief review of the results of the analysis at infrastructure level

Agenda

- Overview of the study and its results
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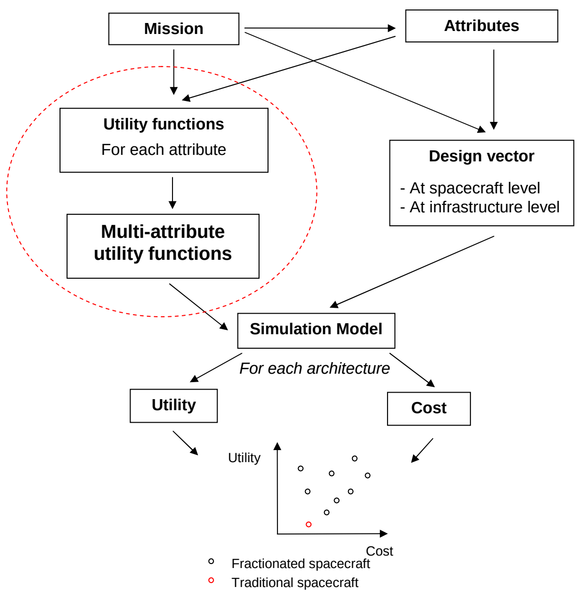
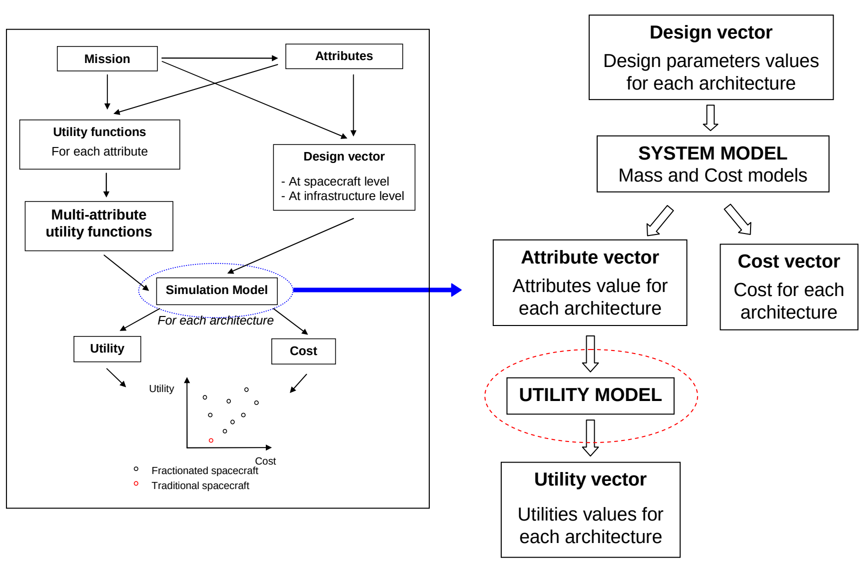
Main research question

When and why is the fractionated spacecraft concept worth being considered as a future way of sending payload on orbit?

Model

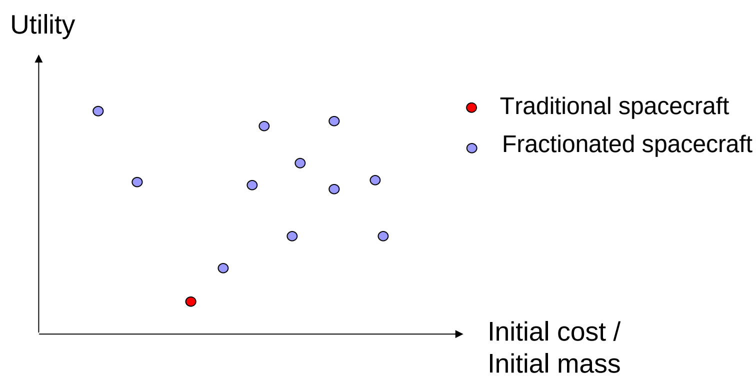


Simulation Model



Expected Results

For each field of application - For a given initial payload



- ⇨ *Demonstration of the advantages of fractionation*
- ⇨ *Identification in each field of the best architectures*

Agenda

- Overview of the study and its results
- Utility interviews
- Brief review of the results of the analysis at infrastructure level

Goal of the utility interviews

To determine the single and multi-attribute utility functions

Of experts in the 3 fields investigated

- Telecommunications
- Sensing
- Navigation

For the 6 following attributes:

- Maintainability
- Scalability
- Flexibility
- Responsiveness (maintenance)
- Responsiveness (upgrade)
- Responsiveness (exchange)

Method used to determine utility functions

- Lottery Equivalent Probability Method
- Using the following parameters:
  - Cost of the maintenance
  - Cost of the upgrade
  - Cost of the exchange
  - Time necessary for the maintenance
  - Time necessary for the upgrade
  - Time necessary for the exchange

Three-step interview process

- Preliminary explanations and questionnaire
  Questions:
  - to capture the decision-making process
  - on the attributes
  - used to define the interviews' scenarios
- Utility Interviews
  - Single utility functions
    To try to determine customer's:
    - willingness-to-pay
    - value derived from shorter time necessary
  - Multi-attribute utility function
- Review of the results of the interviews by the interviewees

What we need from you

- Experts in the three fields
  - Telecommunications
  - Sensing
  - Navigation
- Time commitment for the interview
- Timeframe of the interview

Agenda

- Overview of the study and its results
- Utility interviews
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Additional Design Parameters at Infrastructure Level

- **Standardization Parameter *s***

  Because of standardization, the common infrastructure modules may be overdesigned for some of the payloads

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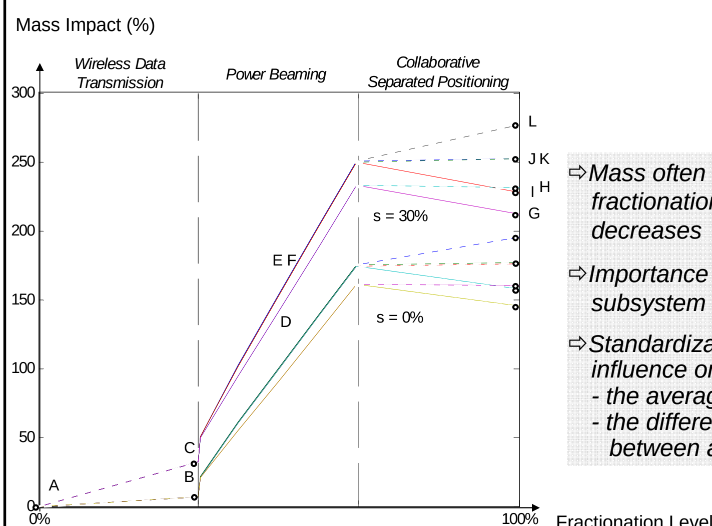

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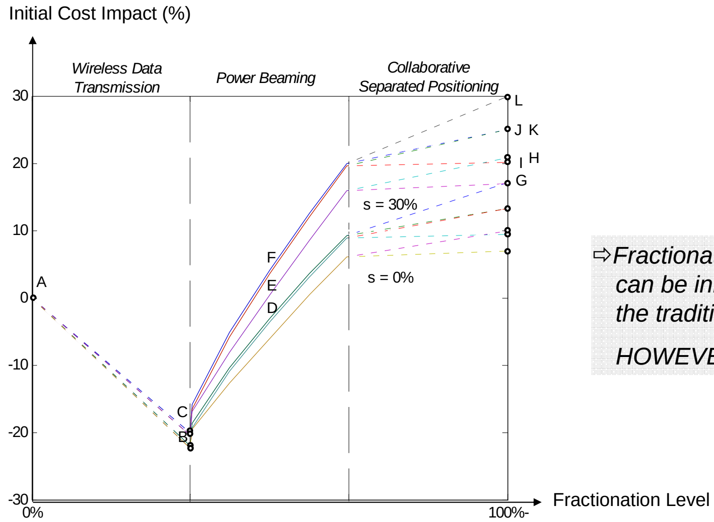

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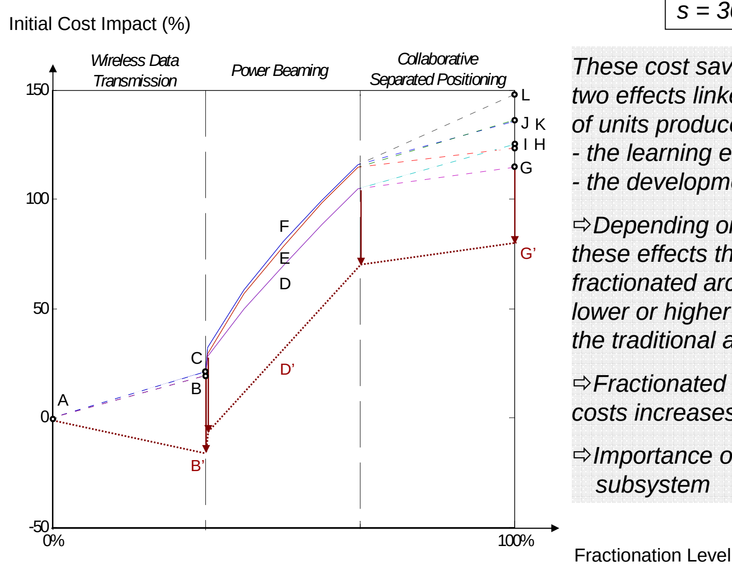

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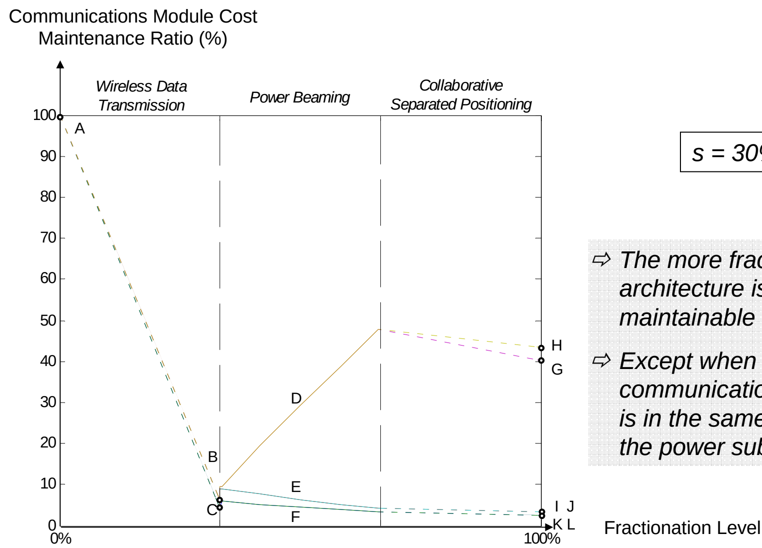

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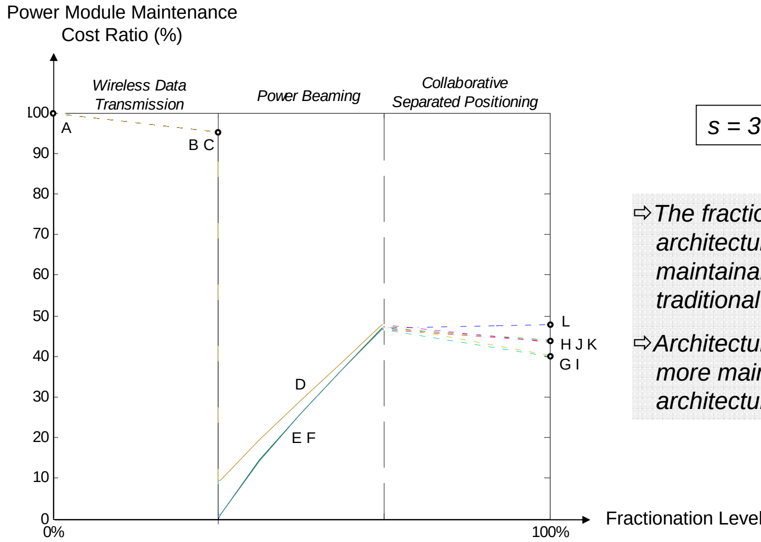

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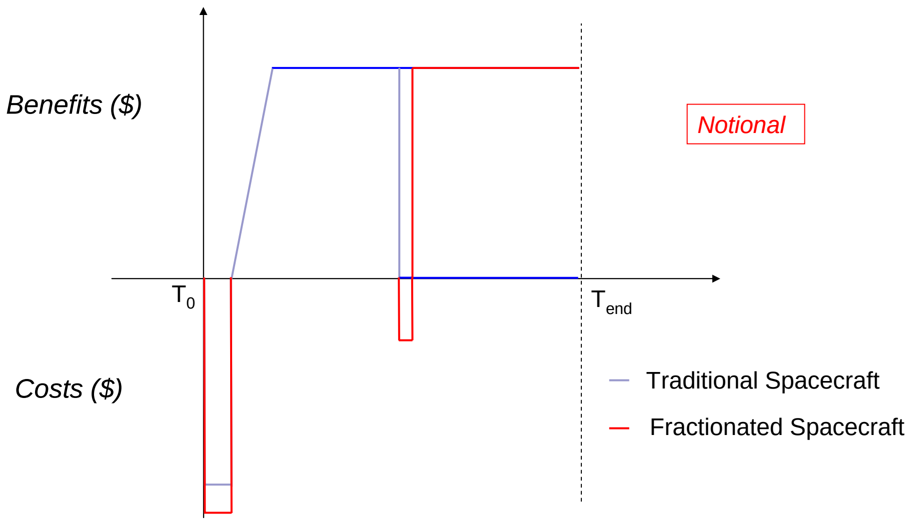
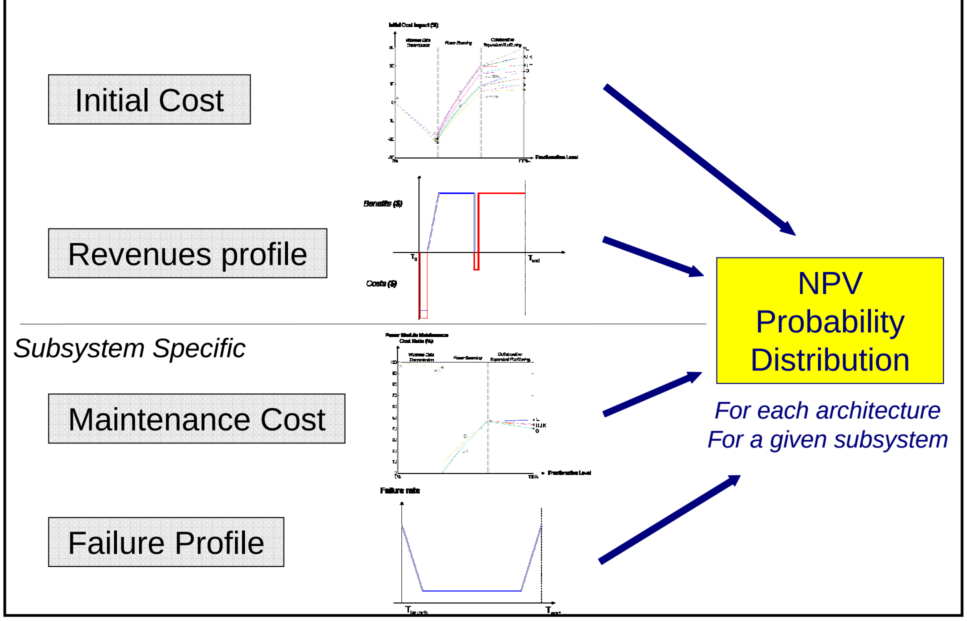


NPV Simulations



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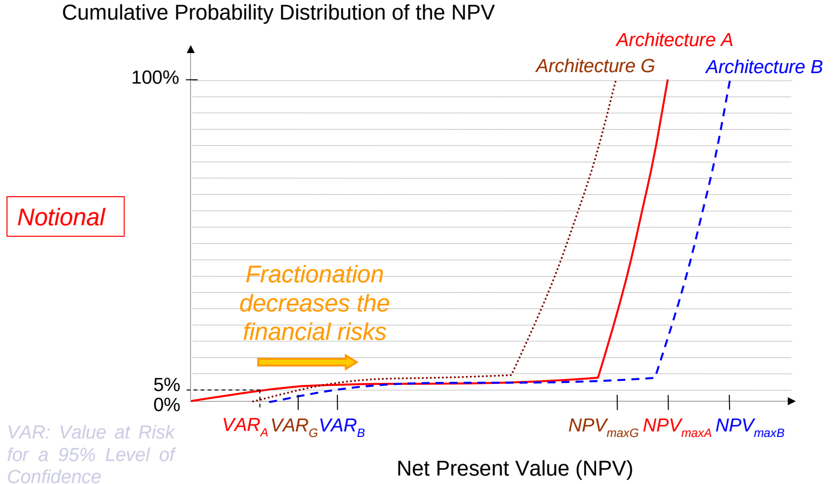

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VI. Customer utility assessment materials: (1) Preliminary explanations, (2) Preliminary questionnaire, and (3) Utility Interviews

Preliminary explanations

What is investigated?

Six types of "flexibility" of space assets are investigated. We want to determine how much you, as a user, value each of them, *independently from how they are implemented*.

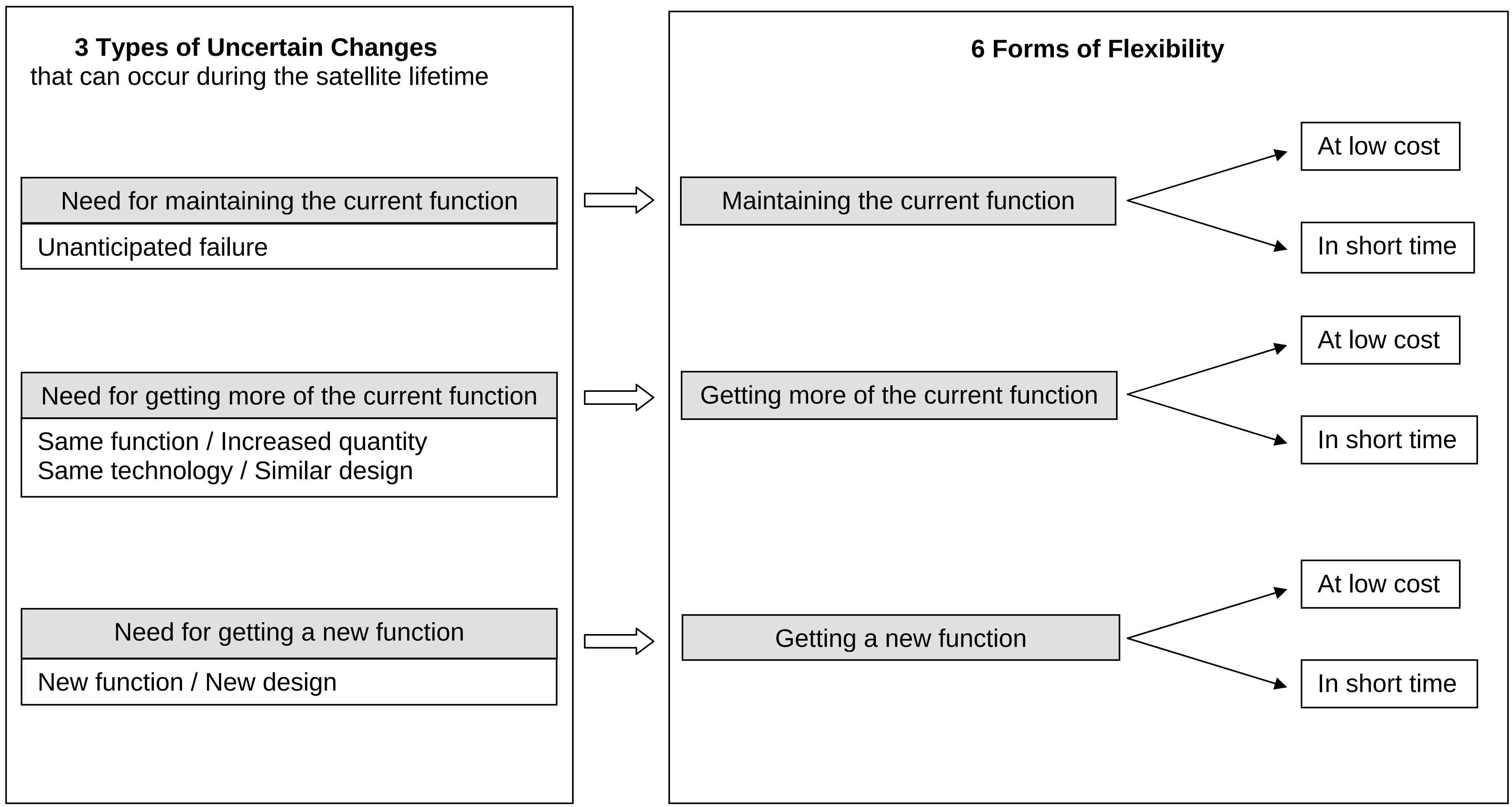
We consider three possibilities associated with the notion of satellite flexibility:

- Maintaining the current function in case of failure
- Getting more of the current function
- Getting a different function

Each of them can be achieved at a given cost and in a given time.

Therefore we will consider six forms of flexibility we would like you to value *independently from each other*:

- The possibility of maintaining the current function cheaply
- The possibility of maintaining the current function quickly
- The possibility of getting more of the current function cheaply
- The possibility of getting more of the current function quickly
- The possibility of getting a different function cheaply
- The possibility of getting a different function quickly


3 Types of Uncertain Changes
that can occur during the satellite lifetime
Need for maintaining the current function
Unanticipated failure
Need for getting more of the current function
Same function / Increased quantity
Same technology / Similar design
Need for getting a new function
New function / New design
6 Forms of Flexibility
Maintaining the current function
At low cost
In short time
Getting more of the current function
At low cost
In short time
Getting a new function
At low cost
In short time

Preliminary questionnaire

1. What is a navigation satellite typical lifetime?
……. Years
2. How would you define the primary function(s) of a navigation satellite?
……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ………………………………………………………………………………………
3. To make sure we are talking about the same forms of flexibility. Could you give me examples from your experience of unanticipated failures of navigation satellite? These are examples in which it would have been desirable to be able to maintain the current function
……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ………………………………………………………………………………………
4. Could you give me examples from your experience of times when there has been a specific need to get more of the current function?
……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ………………………………………………………………………………………
5. What function(s), different from the current one(s), do you think may be needed in the future from a navigation satellite?
……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ………………………………………………………………………………………
6. What type of change(s) is (are) most likely to occur during a navigation satellite lifetime? (Multiple answers possible)
□ Failure – Need to maintain the current function □ Need to get more of the current function □ Need to get a different function
7. What type of change(s) is (are) least likely to occur during a navigation satellite lifetime? (Multiple answers possible)

◻ Failure – Need to maintain the current function ◻ Need to get more of the current function ◻ Need to get a different function
8. Which possibility do you consider as most valuable for a navigation satellite?
◻ Maintaining the current function ◻ Getting more of the current function ◻ Getting a different function
9. Which possibility do you consider as least valuable for a navigation satellite?
◻ Maintaining the current function ◻ Getting more of the current function ◻ Getting a different function
10. Could you rank the 6 forms of flexibility in order of importance to you? From the most important (1) to the least important (6)? => FIG
…... Maintaining the current function cheaply …... Maintaining the current function quickly ..…. Getting more of the current function cheaply …... Getting more of the current function quickly …... Getting a different function cheaply …... Getting a different function quickly
11. In case of failure, in your decision you will consider the costs of maintaining your satellite. What costs would you mainly take into account? (Multiple answers possible)
◻ Manufacturing costs ◻ Integration, assembly, and test costs ◻ Launch costs ◻ Other costs: …………………………………..
12. In case of failure, in your decision you will consider the time necessary to maintain your satellite. What times would you take into account? (Multiple answers possible)
◻ Manufacturing time ◻ Integration, assembly, and test time ◻ Launch time ◻ Other time: …………………………………..
13. If you need more of the current function, in your decision you will consider the corresponding costs. What costs would you include? (Multiple answers possible)

- ◻ Development costs
- ◻ Manufacturing costs
- ◻ Integration, assembly, and test costs
- ◻ Launch costs
- ◻ Other costs: …………………………………..

14. If you need more of the current function, in your decision you will consider the time necessary to obtain it. What times would you include? (Multiple answers possible)

- ◻ Satellite development time
- ◻ Satellite manufacturing time
- ◻ Satellite integration, assembly, and test time
- ◻ Satellite launch time
- ◻ Other time: …………………………………..

15. If you need a different function, in your decision you will consider the corresponding costs. What costs would you include? (Multiple answers possible)

- ◻ Satellite development costs
- ◻ Satellite manufacturing costs
- ◻ Satellite integration, assembly, and test costs
- ◻ Satellite launch costs
- ◻ Other costs: …………………………………..

16. If you need a different function, in your decision you will consider the time necessary to obtain it. What times would you include? (Multiple answers possible)

- ◻ Satellite development time
- ◻ Satellite manufacturing time
- ◻ Satellite integration, assembly, and test time
- ◻ Satellite launch time
- ◻ Other time: …………………………………..

17. How would you describe a standard navigation satellite? In terms of mass, power, , level of performance, cost ,etc.

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

18. How long would it typically take for such a navigation satellite to be developed (from conceptual design to its delivery)?

……. Years
19. Once designed, how long would it typically take for such a navigation satellite to be manufactured (from beginning of manufacturing process to its delivery)?
……. Years
20. Under nominal conditions, what is the likelihood of unanticipated failure of such a navigation satellite?
…………………………………………………………………………………………
21. Would the failure tend to be only partial or complete?
□ Complete □ Partial
22. What is the impact of the failure of one satellite of the constellation?
………………………………………………………………………………………… ………………………………………………………………………………………… ………………………………………………………………………………………… …………………………………………………………………………………………
23. When would you expect the satellite to fail? Please represent the periods during which it is <u>most</u> and <u>least</u> likely to fail or a failure profile on the timelines below.
Launch *End of lifetime*
24. Which subsystems are most likely to fail? Please rank them from the most to the least likely. => FIG
….. Payload ….. Power ….. Communications ….. Control and Data Handling ….. Propulsion ….. Attitude Determination and Control ….. Thermal
25. What is the likelihood of failure of these subsystems during the navigation satellite lifetime? (as a percentage or as an absolute value)

Payload.………

Power.………

Communications.………

Control and Data Handling.………

Propulsion.………

Attitude Determination and Control.………

Thermal.………

26. Each of these subsystems may partially or completely fail. Will the failure of each of these subsystems more likely lead to a partial or complete failure of the whole system?

Payload
□ Complete □ Partial .…% of the initial capacity lost
Power
□ Complete □ Partial .…% of the initial capacity lost
Communications
□ Complete □ Partial .…% of the initial capacity lost
Control and Data Handling
□ Complete □ Partial .…% of the initial capacity lost
Propulsion
□ Complete □ Partial .…% of the initial capacity lost
Attitude Determination and Control
□ Complete □ Partial .…% of the initial capacity lost
Thermal
□ Complete □ Partial .…% of the initial capacity lost

27. When would you expect these subsystems to fail? Please represent the periods during which they are most and least likely to fail or a failure profile on the timelines below.
=> FIG

Payload

Launch *End of lifetime*

Power

Launch *End of lifetime*

Communications

Launch *End of lifetime*

Control and Data Handling

Launch *End of lifetime*

Propulsion

Launch *End of lifetime*

Attitude Determination and Control

Launch *End of lifetime*

Thermal

Launch *End of lifetime*

28. What is (are) the main metrics you would use to define a navigation satellite performance?

……………………………………………………………………………………………

29. During the satellite lifetime, you may need more of the current function, for instance an improved availability (time or geography). How many more satellites may you need? What is the current availability / coverage? Which new regions may be of interest ? *What is the range of additional performance you would expect to be needed? What would be a most likely value? Please define it as a percentage of the initial performance level.*
…………………………………………………………………………………………… …………………………………………………………………………………………… …………………………………………………………………………………………… Range: + ………..% to +……..……% Most likely value: + ………..%
30. Given what you know today, how likely is it that we are going to need only the functions implemented today from the satellite for its entire lifetime?
□ Very unlikely □ Unlikely □ Likely □ Very Likely
31. We considered three types of changes. Do you see any other uncertain change that should be considered?
…………………………………………………………………………………………… …………………………………………………………………………………………… ……………………………………………………………………………………………
32. As a decision-maker, in case of unanticipated failure, on what criteria would you decide to maintain the current function?
…………………………………………………………………………………………… …………………………………………………………………………………………… ……………………………………………………………………………………………
33. As a decision-maker, if you need more of the current function, on what criteria would you decide to get more of the current function?
…………………………………………………………………………………………… …………………………………………………………………………………………… ……………………………………………………………………………………………
34. As a decision-maker, if you need a different function, for instance XXXXXXXX, on what criteria would you decide to get a different function?
…………………………………………………………………………………………… …………………………………………………………………………………………… ……………………………………………………………………………………………
35. What would be the most acceptable cost to maintain the current function of a navigation satellite in case of failure? For instance as a percentage of satellite initial cost or as an absolute value.
……………………………………………………………………………………………
36. What would be the least acceptable cost to maintain the current function of a navigation satellite in case of failure? For instance as a percentage of satellite initial cost or as an absolute value.

……………………………………………………………………………………………
37. What would be the most acceptable cost to get more of the current function of a navigation satellite? For instance as a percentage of satellite initial cost or as an absolute value.
……………………………………………………………………………………………
38. What would be the least acceptable cost to get more of the current function of a navigation satellite? For instance as a percentage of satellite initial cost or as an absolute value.
……………………………………………………………………………………………
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……………………………………………………………………………………………
40. What would be the least acceptable cost to get a different function? For instance as a percentage of satellite initial cost or as an absolute value.
……………………………………………………………………………………………
41. What would be the most acceptable time necessary to maintain the current function of a navigation satellite in case of failure? For instance as a percentage of satellite initial time to delivery or as an absolute value.
……………………………………………………………………………………………
42. What would be least acceptable time necessary to maintain the current function of a navigation satellite in case of failure? For instance as a percentage of satellite initial time to delivery or as an absolute value.
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…………………………………………………………………………………………

Utility interviews

I - Single attribute utility functions

A. Maintainability

Goal: Try to determine customer's willingness-to-pay to maintain the current function

a. Scenario definition

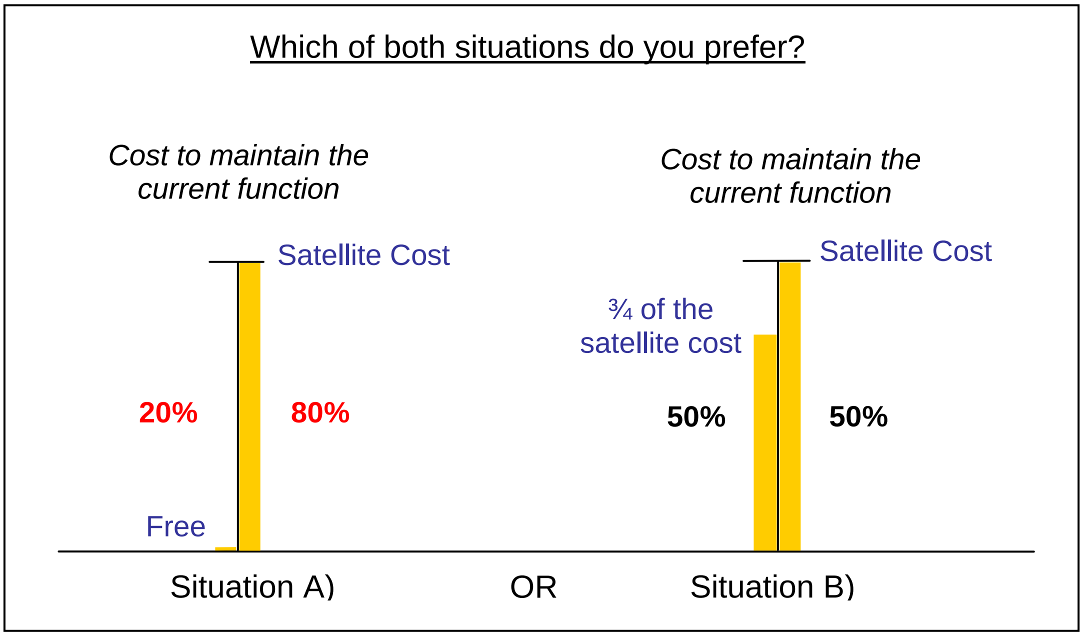
- Given function at a given performance level
- Given lifetime
- Given initial cost of the satellite
- Given failure profile and failure consequences (i.e. failure occurring at time T leading to a complete spacecraft failure)

b. WTP/Probability pairs determination

- Choose a **cost C_1**

"Which of the following situations do you prefer?
*Situation A) **20%** chance of maintaining the current function for C_{best} & **80%** chance of maintaining the current function for C_{worst}*
*Situation B) 50% chance of maintaining the current function for **cost C_1** & 50% chance of maintaining the current function for C_{worst}"*

⇨ determine **$P(C_1)$**



- Choose **cost C_2**

⇨ determine **$P(C_2)$**

B. Scalability

Goal: Try to determine customer's willingness-to-pay to get more of the current function

a. Scenario definition

- Given function at a given performance level
- Given lifetime
- Given initial cost of the satellite
- **Given Δcapacity at a time T**

b. WTP/Probability pairs determination

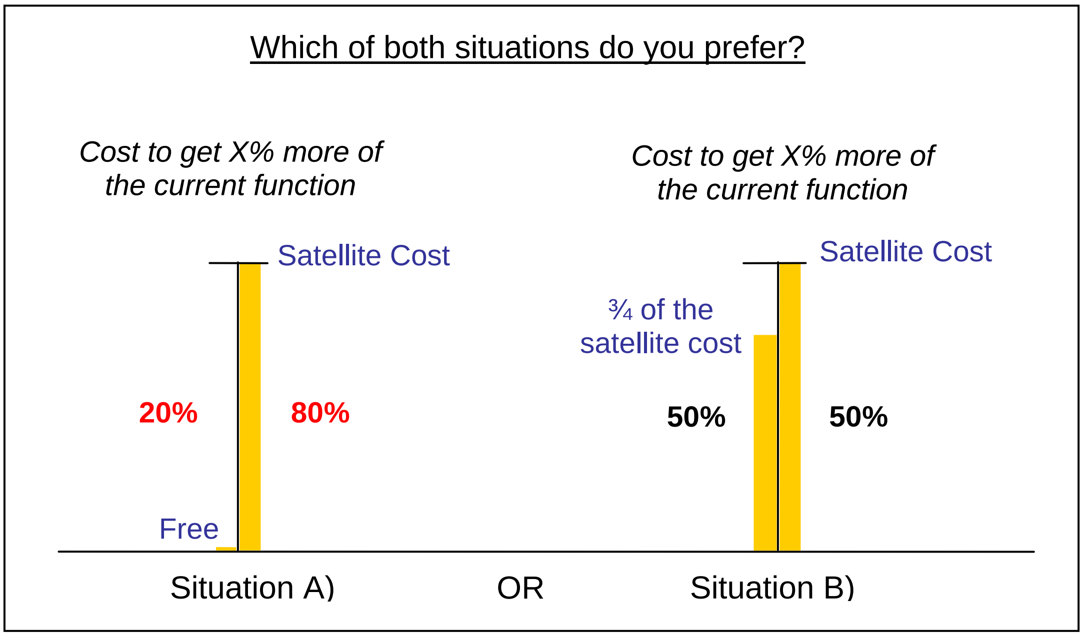
- Choose a **cost C_1**

"Which of the following situations do you prefer?

Situation A) ***20%*** *chance of getting X% more of the current function for C_{best} &* ***80%*** *chance of getting X% more of the current function for C_{worst}*

Situation B) 50% chance of getting X% more of the current function for ***cost C_1*** *& 50% chance of getting X% more of the current function for C_{worst}"*

⇨ determine **P(C_1)**



- Choose **cost C_2**

⇨ determine **P(C_2)**

C. Flexibility

Goal: Try to determine customer's willingness-to-pay to get a different function

a. Scenario definition

- Given function at a given performance level
- Given lifetime
- Given initial cost of the satellite
- **Given new function at equivalent performance level at T**

b. WTP/Probability pairs determination

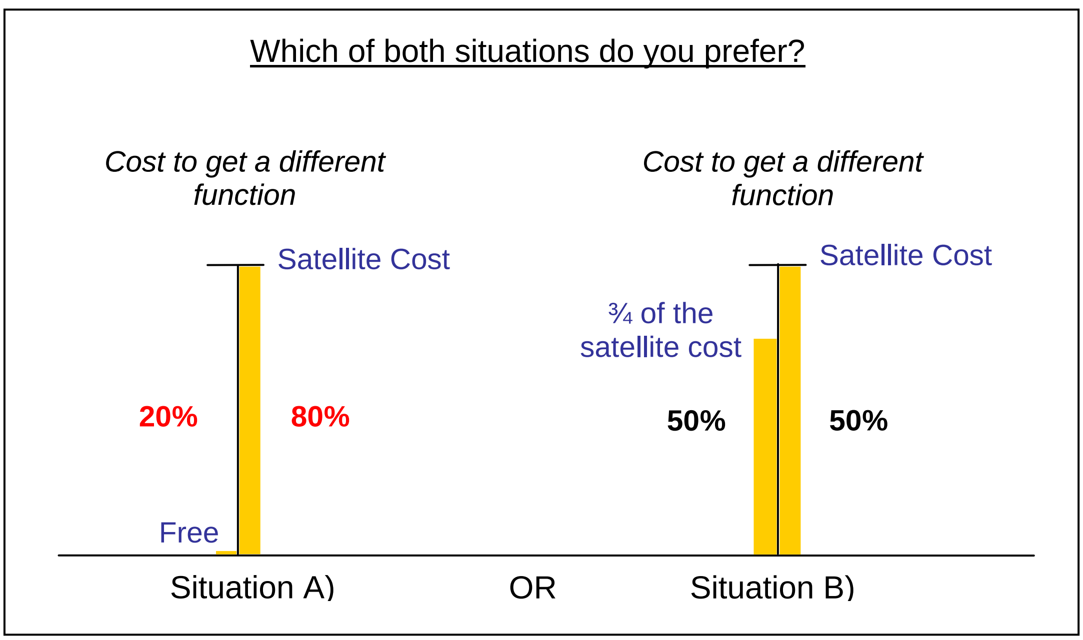
- Choose a **cost C_1**

"Which of the following situations do you prefer?

*Situation A) **20%** chance of getting a different function for C_{best} & **80%** chance of getting a different function for C_{worst}*

*Situation B) 50% chance of getting a different function for **cost C_1** & 50% chance of getting a different function for C_{worst}"*

⇨ determine **P(C_1)**



- Choose **cost C_2**

⇨ determine **P(C_2)**

D. Responsiveness associated with maintainability

Goal: Try to determine value derived by the customer from shorter time to maintain the current function.

a) Scenario definition

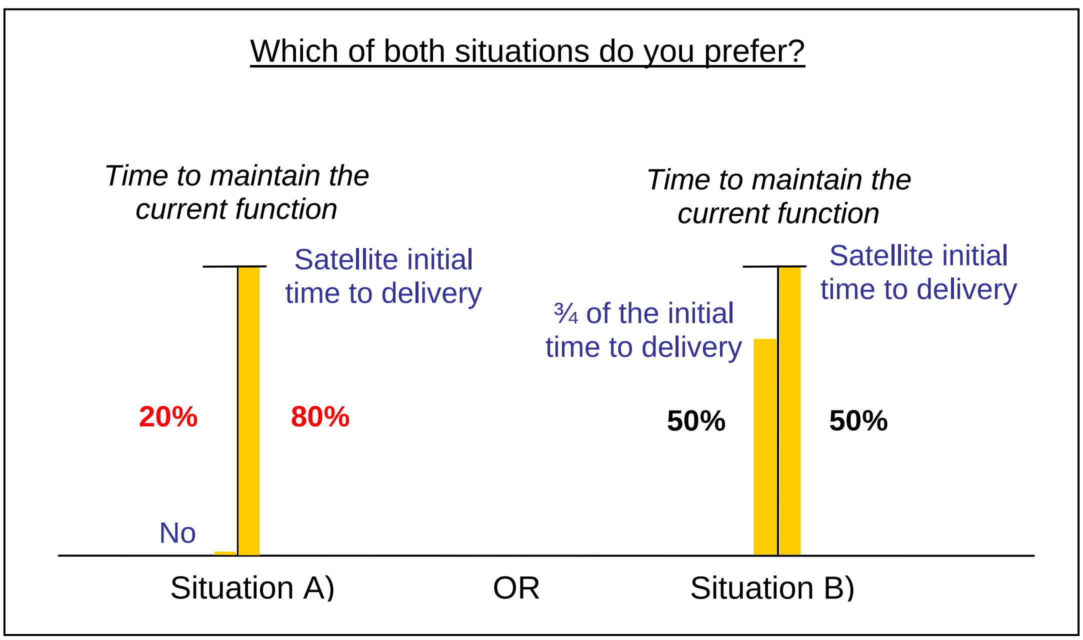
- Given function at a given performance level
- Given lifetime
- Given time necessary to initially get the satellite
- **Given a failure at a time T**

b) WTP/Probability pairs determination

- Choose a **time T_1**

"Which of the following situations do you prefer?
*Situation A) **20%** chance of maintaining the current function in T_{best} & 80% chance of maintaining the current function in T_{worst}*
*Situation B) 50% chance of maintaining the current function in **time T_1** & 50% chance of maintaining the current function in T_{worst}"*

⇨ determine **P(T_1)**



- Choose **time T_2**

⇨ determine **P(T_2)**

E. <u>Responsiveness associated with scalability</u>

Goal: Try to determine value derived by the customer from shorter time to get more of the current function

a) Scenario definition

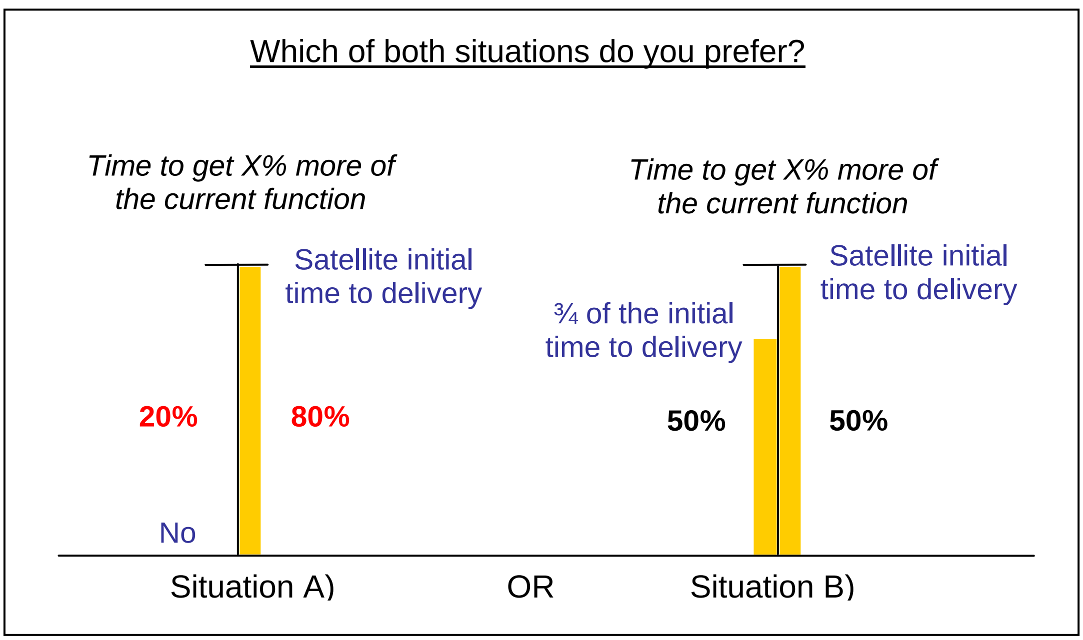
- Given function at a given performance level
- Given lifetime
- Given time necessary to initially get the satellite
- **Given Δcapacity at a time T**

b) WTP/Probability pairs determination

- Choose a **time T_1**

"Which of the following situations do you prefer?
*Situation A) **20%** chance of getting X% more of the current function in T_{best} & 80% chance of getting X% more of the current in T_{worst}*
*Situation B) 50% chance of getting X% more of the current in **time T_1** & 50% chance of getting X% more of the current in T_{worst}"*

⇨ determine **P(T_1)**



- Choose **time T_2**

⇨ determine **P(T_2)**

F. <u>Responsiveness associated with flexibility</u>

Goal: Try to determine value derived by the customer from shorter time to get a different function

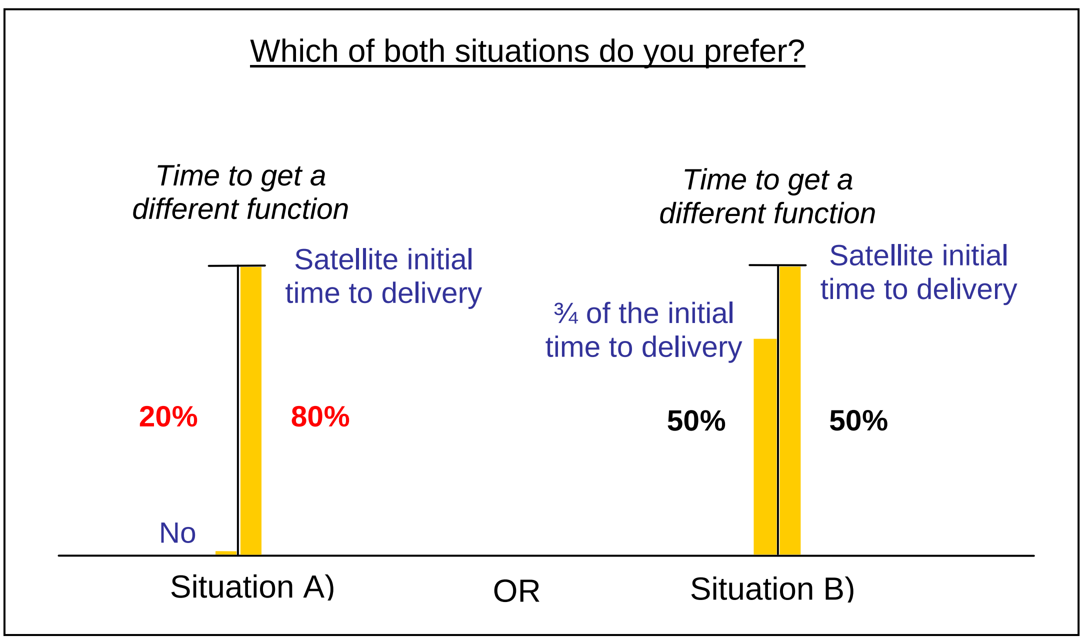
a) *Scenario definition*
- Given function at a given performance level
- Given lifetime
- Given time necessary to initially get the satellite
- **Given new function at equivalent performance level**

b) *WTP/Probability pairs determination*

- Choose a **time T_1**

"Which of the following situations do you prefer?
*Situation A) **20%** chance of getting a different function in T_{best} & 80% chance of getting a different function in T_{worst}*
*Situation B) 50% chance of getting a different function in **time T_1** & 50% chance of getting a different function in T_{worst}"*

⇨ determine **P(T_1)**



- Choose **time T_2**

⇨ determine **P(T_2)**

II - Multi-attribute function

Goal: Determine the 6 k_i

<u>Determination of the parameter k_i associated with maintainability</u>

"Which of the following situations do you prefer?

Situation A) *Maintaining the current function for C_{best} and T_{worst} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{worst} in T_{worst}*

Situation B) ***20%** chance of maintaining the current function for C_{best} in T_{best} & getting X% more of the current function for C_{best} and time T_{best} & getting a different function for C_{best} in T_{best} AND **80%** chance of maintaining the current function for C_{worst} in T_{worst} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{worst} in T_{worst}"*

⇨ $P_i = k_i$

<u>Determination of the parameter k_i associated with maintainability</u>

Situation A) *Maintaining the current function for C_{best} and T_{worst} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{worst} in T_{worst}*

Situation B)

<u>Determination of the parameter k_i associated with scalability</u>

Situation A) *Maintaining the current function for C_{worst} and T_{worst} & getting X% more of the current function for C_{best} and time T_{worst} & getting a different function for C_{worst} in T_{worst}*

Situation B)

<u>Determination of the parameter k_i associated with flexibility</u>

Situation A) *Maintaining the current function for C_{worst} and T_{worst} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{best} in T_{worst}*

Situation B)

<u>Determination of the parameter k_i associated with responsiveness (maintainability)</u>

Situation A) *Maintaining the current function for C_{worst} and T_{best} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{worst} in T_{worst}*

Situation B)

Determination of the parameter k_i associated with responsiveness (scalability)

Situation A) *Maintaining the current function for C_{worst} and T_{worst} & getting X% more of the current function for C_{worst} and time T_{besst} & getting a different function for C_{worst} in T_{worst}*

Situation B)

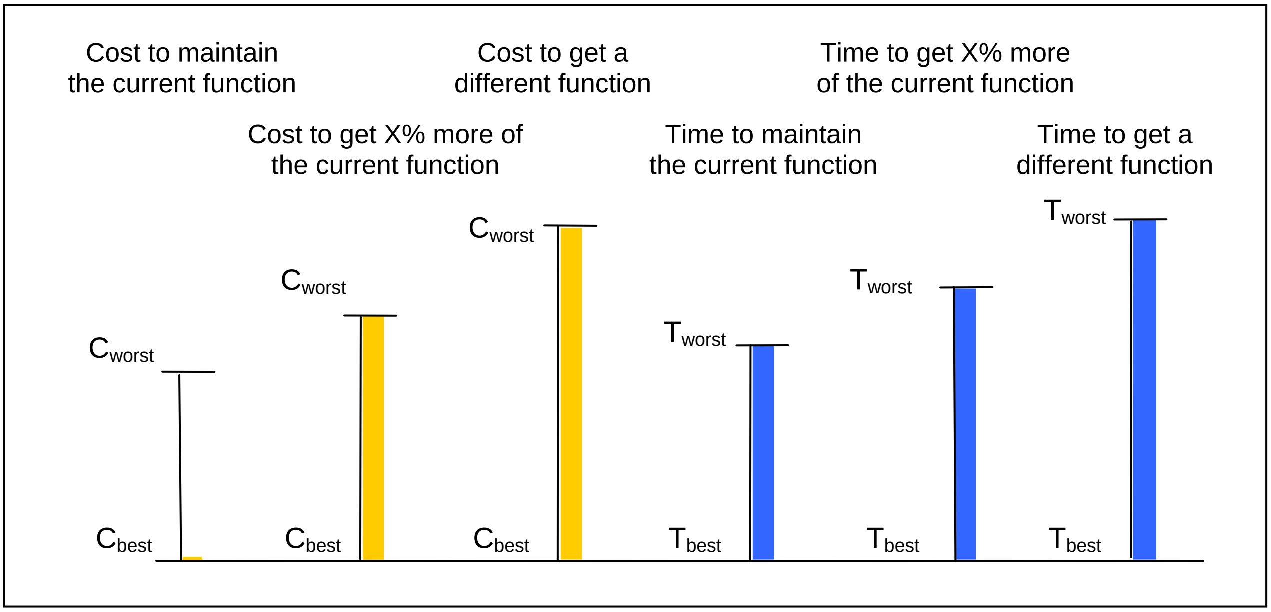
Determination of the parameter k_i associated with responsiveness (flexibility)

Situation A) *Maintaining the current function for C_{worst} and T_{worst} & getting X% more of the current function for C_{worst} and time T_{worst} & getting a different function for C_{worst} in T_{best}*

Situation B)

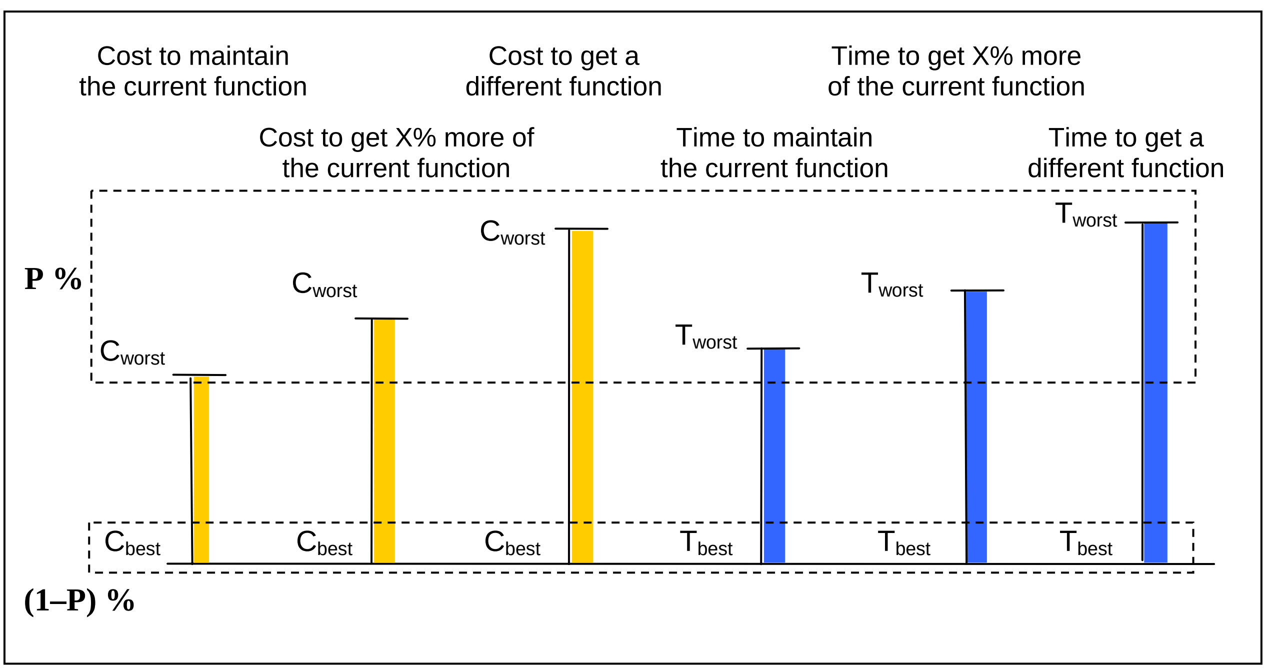
<u>Which of both situations do you prefer?</u>

Situation A)



OR

Situation B)



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