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“Multi Disciplinary Design Optimization and appropriate recommendations to DLR Engineering Processes”

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ORIGINALITY STATEMENT

I, Oscar Sanabria, herewith declare that I have completed the present Master thesis "Multi Disciplinary Design Optimization and appropriate recommendations to DLR Engineering Processes" independently, making use only of the specified literature and aids. Sentences or parts of sentences quoted literally are marked as quotations; identification of other references with regard to the statement and scope of the work is quoted. The thesis in this form or in any other form has not been submitted to an examination body and has not been published.

Bremen, Germany 09.11.2020

Place, Date

Signature

DEDICATION

Para Amelia, mi hija, este es el fruto del esfuerzo de tus abuelos, mamá y papá, hemos querido enseñarte a seguir tus sueños, siempre.

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This work was performed during my time as a master student in cooperation with the German Aerospace Center (DLR). A great thanks to all those who supported me in my work and without whom this work would not have been possible.

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ABSTRACT

Concurrent Engineering is the established methodology for the early design phase of space missions. An interdisciplinary team covering several domains (e.g. propulsion, mission analysis, communications, systems) is a vital part of the process coming along with multiple interconnected design variables and individual dependencies for each mission.
Enabling the concurrent design team to create a quantifiable concept, instead of only one consistent design based on 'engineering intuition', and allowing for an optimization on systems level, instead of letting the domain experts optimize their subsystems only, would lead to a major improvement of the process.

The key element therefor is Multidisciplinary Design Optimization (MDO), which is a formal methodology with its origin in the 90th for finding optimum system level solutions involving multiple interrelated subsystems, domains or disciplines.

The aim of this thesis is to create a comprehensive map of existing MDO techniques beginning from the 90th up to the newest trends that can be found in the international research landscape, cluster them via their methodology and what they can be used for, to in the end be able to make a recommendation for the use in the DLR Concurrent Engineering process.

In order to successfully achieve the aim of this thesis, 5 chapters are structured. Chapter 1 describes the history of MDO and gives context regarding the why this design concept was created and how it has gradually been utilized in the Aerospace industry. Chapter 2 provides some necessary context to understand the overall functioning and structure of the different MDO methodologies existent and classifies them for the easy understanding of their characteristics, while also selecting the ones that after the review of 49 scientific papers and several online lectures, are better suited to be used in the Concurrent Engineering process of DLR. Chapter 3 is then focused on explaining the generalities and mathematic of each of the pre-selected MDO methods in chapter 2 and brings insights as the advantages and drawbacks and depicts clearly a map of their possible uses in the Concurrent Engineering process of DLR. Chapter 4 is a description of the Concurrent Engineering process of DLR, its aim and the resources available for the different studies performed thus creating the necessary context to in Chapter 5 enumerate the necessary recommendations and conclusions for a successful implementation of the MDO methods mapped in chapter 3 in the Concurrent Engineering process of DLR as well as important remarks regarding the necessary studies needed in order to do so.

Chapter 5 shows why after a thoughtful qualitative analysis of DLR Concurrent Engineering process and facilities, the recommendation for the use of Bi-level integrated system synthesis 2000 (BLISS-2000) is the most suitable MDO as of the view of this author, after reviewing the literature available BLISS-2000 shows several similitudes with the CE process of DLR and more so allows the combination of the other MDO methods at a sub level of the optimization method that fits right into the CE processes currently performed in the space vehicle design studies.

Important emphasis is also stated in the conclusions of this document as of the necessity to realized further quantitative studies, the suggested way is a retroactive analysis of the available study cases already performed by DLR, in which the MDO methods here selected in chapter 3 are adapted to each study and run in parallel in order to have numerical data and perform a benchmarking on performance and cost of implementation vs the gains in design optimization.

INTRODUCTION

Over the past decades, space vehicle design for space missions has changed significantly, these changes involve several advances in specific fields encompassing the different domains of it. These improvements are reliant on the state-of-the-art computational technologies at hand for simulation and prediction of outcomes of the main design decisions, these computational improvements play a decisive roll not just in aiding human decision making but also in the design methodology itself.

No matter how advanced computational design aids had become, there is still a large human interaction in the top designing process of our time, thus some of the main design decisions depend on acquired knowledge and experience as well as “Engineering intuition” from the members of the designing team.

The German Aerospace Center (DLR) in particular uses an Concurrent Engineering (CE) Design approach when dealing with Space mission design projects, CE combines several domains (i.e. propulsion, mission analysis, communications, etc.) regarded with the conceptual design of a space mission that is able to coordinate a successful interaction between disciplines to achieve a feasible conceptual design generated in a reasonable time frame by working concurrently instead of sequentially.

Rather CE design reaches optimality and not just feasibility is a question most likely answered confirming that optimality is at least assumed however unknown, while feasibility is of course assured. Hence the need to enable the CE design team to create a quantifiable optimal conceptual design, instead of only one consistent feasible design based on the “Engineering intuition” of a group of experts and allowing for an optimization on systems level. The key selected element therefor is Multidisciplinary Design Optimization (MDO), which is a formal set of methodologies with its origin in the 90s for finding optimal system level solutions involving multiple interrelated subsystems, domains or disciplines.

This Master Thesis provides a summary of the history of MDO, an explanation of the concept behind it and a qualitative survey of the current MDO methodologies that are regarded as suitable, available and relevant for the CE design process as of the author opinion. Surveys of the different MDO methodologies had already been conducted before as in Cramer et al. (1994) and Balling and Sobieski (1996) to name some, however this studies are either not complete (do not include all MDOs currently available) or not directed to the specific problem address in this thesis, which main aim is: a comprehensive mapping of existing MDOs techniques from its origins to the latest trends found in the international research landscape, and to derived from it a set of conclusions and recommendations for the successful MDO use and implementation in the DLR CE process.

The investigation performed in this thesis shows that even though there is a broad spectrum of MDO methods currently available, such as described in Martins and Lambe (2013) and Balesdent et al. (2011), the main gain from them in terms of finding an optimal design, depends highly in the problem being formulated, thus a specific method is unlikely to give the best results for all design projects in the DLR CE process, but, based on a close view and qualitative analysis of the particularities of the DLR CE process, a selection can be made as of the most promising ones, and recommendations as of the way forward can be made.

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ABREVIATIONS

AAO: All At Once
ATC: Analytical Target Cascading
BLISS: Bi-Level System Synthesis
CO: Collaborative Optimization
CSSO: Concurrent SubSpace Optimization
DIVE: Discipline Interaction Variable Elimination
DV: Design Variables
FPI: Fixed Point Iteration
GA: Genetic Algorithm
GSE: Global Sensitivity Equation
IDF: Individual Discipline Feasible
MCO: Modified Collaborative Optimization
MDA: Muldisciplinary Design Analysis
MDF: Multi Discipline Feasible
MDO: Multidisciplinary Design Optimization
MOPCSSO: Multi-Objective Pareto CSSO
NAND: Nested Analysis and Design
OBD: Optimization Based Decomposition
RSM: Response Surface Method
SAND: Simultaneous Analysis and Design
SQP: Sequential Quadratic Programming
SNN: Single NAND NAND
SSA: System Sensitivity Analysis
SSN: Single SAND NAND
SSS: Single SAND SAND
Dyleaf: Dynamic Leader Follower
QSD: Quasi-Separable Decomposition
MDOIS: MDO of independent subspaces
IPD: Inexact Penalty Decomposition
EPD: Exact Penalty Decomposition
ECO: Enhanced Collaborative Optimization
ASO: Asymmetric Subspace Optimization
IPSP: Initiation, Preparation, Study and Processing
M: Milestone achieved
XDSM: Extended Design Structure Matrix
CE: Concurrent Engineering
DOE: Design of Experiment
DLR: Deutsches Zentrum fur Luft und Raumfahrt

CHAPTER 1: MULTIDISCIPLINARY DESIGN OPTIMIZATION HISTORY

1. MDO techniques.

The existence of optimization methods is as old as math itself, hence an important differentiation between Multidisciplinary Optimization techniques and Optimization techniques needs to be made clear, thus even when both can be used in combination, MDO and its different variants are relatively much more recent and are still a research topic for which there is still room for further studies, while optimization methods have been around since the times of Isaac Newton, in fact one of the methods that will be address in this thesis track its roots from him regarding its formulation (Newton method for numerical optimization).

The first documented step in the application of combined optimization in our modern times was in structural design in the 1960s when Schmit LA (1960) in his work “Structural design by systematic synthesis” proposed a new approach in order to find optima when designing structures and dealing with multiple variables. This was the conceptual foundation that allowed for the development and introduction of the idea of feasibility for coupling finite element structural analysis and non-linear mathematical programming, in order to have a tool dedicated to the search of automated optimum design capabilities.
Analytical and numerical structural optimizations were also approached by Prager (1968) and Venkayya (1968), thus introducing the notions of natural separation of the design problem but both application and research remained in the field of structural analysis.

The first known breach of combined optimization (multiple variables, non-linear mathematical programming) outside pure structure design was documented by Sobieszczanski–Sobieski et al. (1982) when he applied it for the design of fuselage structures, in this paper the structure design was performed in two stages, first an over-all distribution of structural material was obtained by means of optimality criteria meeting specific constrains, and second, a detailed design for the combination of skin and stringers is performed by mathematical optimization accounting for realistic design constraints.
This although remains in the field of structure optimization, brings the method to a different overall discipline such as Aeronautics (aircraft wing design) and thus opened the door to its further application on this discipline, successfully combining aerodynamics, structures, and controls as strongly coupled disciplines.

The evolution of MDO techniques have been influenced in the greater part by the improvements that had taken place in the computing capabilities available at each period of time since the early stages, but in the 90s and all the way into the 2000s the greater and broader spectrum of different formulations of the MDO applications can be seen, concurrent with the same rise in computer computation improvement.
New approaches were developed into much more complex formulations, as far as the computing systems were able to handle, and much of the effort in these developments involved the usage of algorithms for the calculations of optima, thus stimulating the break of decomposition methods intended to aid the efficiency of performing these large tasks

into sets of smaller ones while preserving couplings as addressed in Balling et al. (1996), overall a clear distinction could now be made between the original formulations in the 70s and the new methods, that pursued not just an optimal feasible solution but also the most reliable, feasible and efficient (both in cost and time) way of finding this optima.

In its assessment on the state and future advancement of MDO Agte et al. (2009) present what can be considered nowadays, a very good description of the timeline MDO has followed since its origins, as depicted in figure 1.

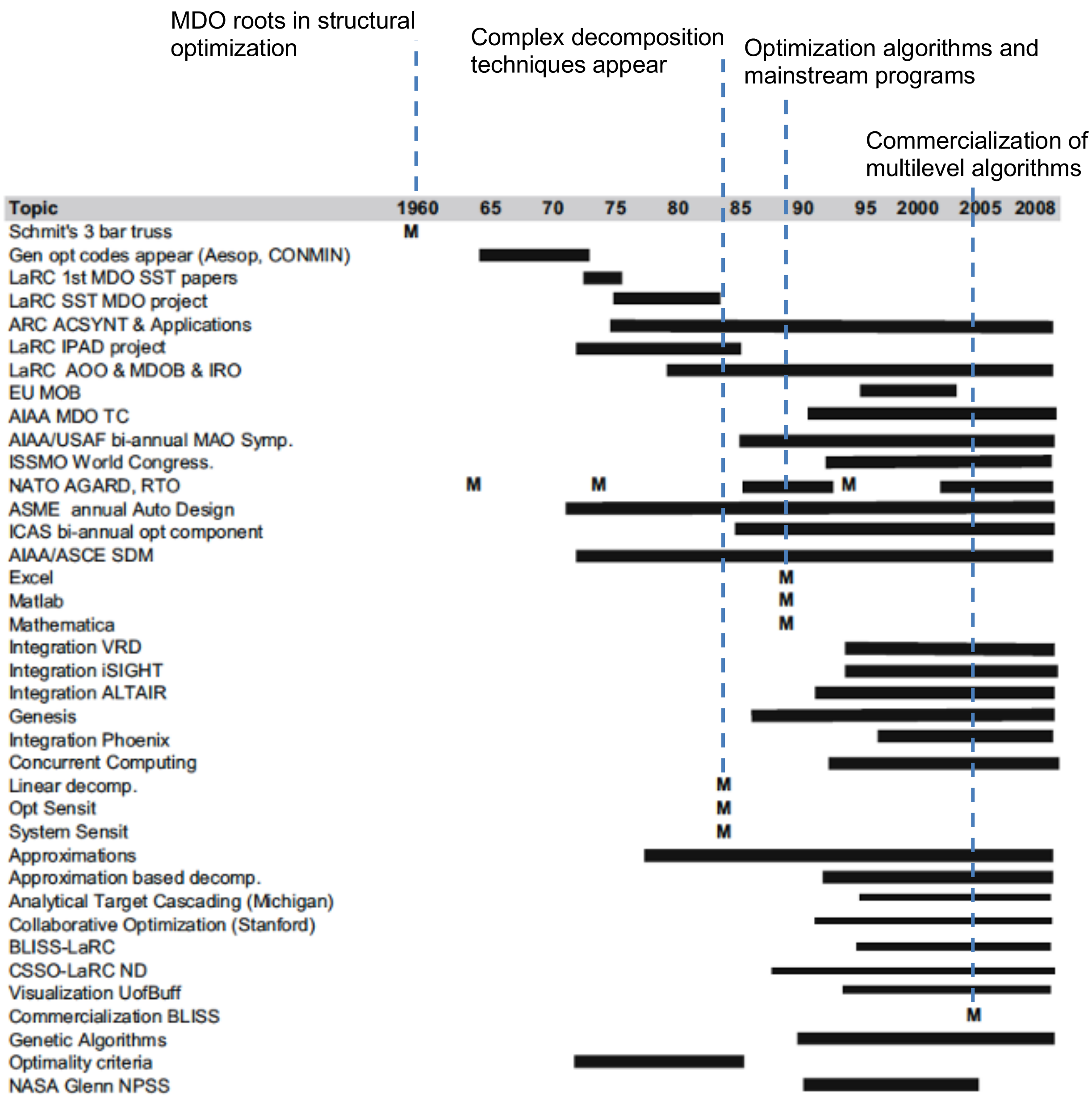

Figure 1. MDO time line from Agte et al.(2009) with modifications; M stands for each important mile stone in the timeline.

It is very important to notice that MDO techniques as stated above, gained momentum starting in the end of the 80s and early 90s and from that moment forward are considered and remain the future of design compared to traditional methodologies, especially in the field of aeronautics and aerospace, however is as equally important to duly note that, MDO remains still an unmatured, unfinalized topic, and although after the literature research performed thought this thesis shows a solid and large interest in the scientific community, more needs to be done regarding its widespread dissemination, implementation and standardization, this is in the view of the author of this thesis why its full potential is still not fully developed.

1.1 MDO techniques in Aerospace Vehicle Design.

One of the first applications of MDO in Aerospace was aircraft wing design, where couplings between already very well matured domains such as aerodynamics and structures placed a challenge to Engineers regarding the optimal point for which lift, drag and stress could come together in the most cost efficient and performance efficient way. The result of this search for an optimum that could address all this domains resulted in several studies such as those of Grossman et al. (1988/1990), Livne et al. (1990/1999) to name some, which focused on the integration of more than one discipline into the common objective of finding a most suitable (manufacturing process wise) and optimum wing design.

The thriving and almost exponential evolution of computer sciences experienced in the last 3 decades brought the necessary support tools in order to formulate more and more complex MDO problems, and handle large amount of data in order to come up with MDO technologies that offered solutions to diverse design problems, but the necessity to find the best MDO problem formulation, that allows us to solve for optimality rapidly and efficiently became a dominant trend among scientist as a natural next step, thus leading the way for diverse problem formulations that aimed at decomposing the different problems into smaller ones, doing so, computational resources could be split and not centralized, allowing for better solutions times and least expensive computational investments.

Especially in the field of Aerospace and Aeronautics, there has been an evident evolution of the techniques, these is documented first by Kroo and Manning (2000), but as of the view of this author, it is more accurate to note 3 main Generations as stated by Ciampa and Nagel (2020), that are as follows:

1st Generation of MDO: Integrated MDO systems

This Generation encompasses the first MDO formulations and its main characteristic is to be single level or as referred in other literature monolithic. This generation of MDO formulations tightly integrate disciplinary capabilities and optimizer.

This first Generation MDOs are among the most efficient computationally, from a runtime perspective and have the larger amount of published papers and studies describing performance and comparing the different architectures and its results. They are reliant on efficient optimization algorithms of which some are already embedded in most common programming software, already commercially available. Among this 1st generation of MDOs we could list effectively MDF (Multi Disciplinary Feasible), IDF (Individual Discipline Feasible) and AAO (All At Once) as the most representatives and the ones which have more precedent research performed.

As far as research studies have been reviewed in the frame of this thesis, the first Generation of MDO has successfully proven its worth in fields that do not require handling of large numbers of domains, variables or complex couplings between them. It is thus an excellent departing point for industries such as automotive, however its greatly proven performance typically lacks the agility to exchange and update the subset of the integrated design modules when it is necessary to adapt them to new objectives or configurations; also as described by several of the papers reviewed in the course of this thesis, the first generation MDOs fails to provide good results when the disciplines and effects accounted in the design problem are too many or far too complex, not because the implementation is not possible, but it's just too impractical to formulate, or provide little benefit due to the greater effort that needs to be put in place to formulate it every time it needs to be modified due to needed human interaction in the problem formulation.

2nd Generation of MDO: Distributed MDO systems

This generation of MDO is highly characterized by its distribution of the MDO problem into subsystems modules and the search for more flexibility to exchange and update the subset of the integrated design modules in order to allow for adaptability when needed, as well as parallelism in runtime for calculations and search of optima, without affecting the reconfiguration of the entire design process while still keeping consistency, this latter achieved by the MDO formulation.
These generation also allows for customization and optimization of computer facilities to the requirements of each individual module, and then process all data from the individual domains through a centralized optimizer that also coordinates the interactions between domains to achieve consistency and feasibility.

We can clearly see a focus in improving the formulation (architecture) of the optimization problem structure in order to exploit the different computational capabilities that emerged through the 90s and 2000s, as well as to formulate the MDO problem distribution to adapt easily to the structures of the organizations implementing them. Examples of this generation are the CO (Collaborative Optimization), BLISS-2000 (Bi-Level Integrated System Synthesis-2000) or ATC (Analytical Target Cascading) methods to name some.

3rd Generation of MDO: Collaborative MDO systems

The third generation of MDOs must not be interpreted as a set of new MDO formulations in regards of the architecture, but the development of a set of solutions to the non-technical barriers in which MDO can be developed and applied, such as organization

structures, large data handling and interpretation of results, among the MDO users organizations.
These sets of improvements seat chronologically well as a next generation of MDO and aim to fully unleash the whole potential of the “second generation of MDOs” the main focus thus is to allow MDOs to be a key support tool to “human judgement and to lessen the aforementioned complexities”.

The 3rd generation of MDOs as named by Ciampa and Nagel (2016) is “the development of decomposition methods, such as Concurrent Engineering and Collaborative optimization, which promise to enable the reality of participative engineering”. Thus, chronologically well placed and named in the history of MDO but rather not fully realized yet but sorting the challenges that will propel MDO to achieve its highest benefits.

These evolution viewed here as generations, depict not just the logical evolution of MDO into more complex problem formulation architectures through time, but the increasing need to address more and more complex systems by partitioning strategies that allow for efficient calculations, and efficient searches of optima and adapting the different organizations (for instance DLR) in order to successfully integrate MDO to Aerospace and more so to subtract the better benefit from it.

1.2 Timeline and state of the art in MDO.

When reviewing the history of MDOs it is a logical step to formulate a comprehensive timeline that shows the way in which methodologies had been formulated and thus be able to depict clearly the state-of-the-art methodologies among them. However, there is a conflict at the moment of the writing of this thesis, regarding the existing literature when it comes to labeling the different methodologies/architectures, and there is a lot of room for improvement when it comes to create a standard consensus. In addition, the different MDO methodologies in time cannot and should not be understood as a single finalized finding formalization of a static architecture but as continuously in evolution core architecture, continuously been enhanced and re study by both the new computer developments and mathematical advancement in the form of optimization algorithms.

For the purpose of this thesis in the further chapters a special focus will be on such MDOs that are proven to have worked or could be used in Aerospace applications, due to its core characteristics in the way they are formulated and used. Some of them such as QSD (Quasi Separable Decomposition), IPD/EPD (Exact and Inexact Penalty decompositions), MDOIS (MDO of Independent Subspaces) and ASO (Asymmetric Subspace Optimization), were ruled out because of the way they operate the objective functions and the constraint variables is far away from the main aim of this work, i.e. MDOIS by Shin et al (2005) is an MDO of independent subspaces that is applied when there are no system wide constrains and objectives, as well as not shared design variables in the whole optimization problem between domains, thus being not possible to efficiently use it when considering the DLR Concurrent Engineering (CE) process for space vehicle design.

The previously mentioned exclusions nonetheless have been included in this chapter in table 1, as it is important to depict them as part of the continuously evolving history of the different MDOs which is the aim of this thesis chapter.

Table 1. MDOs timeline as per first publication formally naming them.

MDO Architecture	YEAR OF FIRST PUBLICATION PAPER	AUTHOR
CSSO	1988	Sobieszczanski-Sobieski et al.
MDF (NAND/SNN)	1994	Balling and Sobieszczanski Sobieski,Cramer et al.
IDF (OBD/SAND/SSN)	1994	Cramer et al.
AAO (SSS)	1994	Balling and Sobieszczanski Sobieski,Cramer et al.
SAND	1994	Balling and Sobieszczanski Sobieski,Cramer et al.*
CO	1995	Braun and Kroo.
BLISS	1998	Sobieszczanski-Sobieski et al.
ATC	1999	Michelena et al.
MCO	2000	Miguel and Murray.
BLISS-2000	2003	Sobieszczanski-Sobieski et al.
DyLeaf	2003	Tava and Suzuki .
MOPCSSO	2004	Huang and Bloebaum.
QSD	2005	Haftka, R. T. and Watson.
MDOIS	2005	Shin, M.-K. and Park.
IPD/EPD	2006	DeMiguel, V. and Murray.
DIVE	2006	Masmoudi and Parte.
ECO	2008	Roth and Kroo.
ASO	2009	Chittick, I. R. and Martins.

Despite the effort to construct Table 1 it is improper to set a timeline for all known MDOs, in which it might be understood that each one is a terminated study and formulation, each MDO is a constant subject of improvement and research hence very dynamic in time, for the aim of visualization table 1 presents a summarization of the different MDOs and the year and author of its first publications, then again this should be taken as a mental visualization tool that helps getting an idea of the history of MDOs rather than a formal timeline.

* i.e. what is labeled as AAO in most surveys is also labeled as SAND in others thus changing not just the name but particularities such as the year of first publication, as other such as Balesdent et al. (2011) categorizes this as a single method.

CHAPTER 2: MULTIDISCIPLINARY DESIGN OPTIMIZATION METHODOLOGIES

2. MDOs in scientific literature.

There are several Multidisciplinary Design Optimization methodologies currently available either for research, or commercial purposes, however in this chapter the focus will be on explaining the most important details of the MDOs that best fit the Aerospace industry or that have already been put to use of some designs hence could be considered in order to construct a comprehensive map of MDO techniques that could be used in a Concurrent Engineering design process such as the one in the German Aerospace Center (DLR), which in the next chapter will be explained also in detail.

From the 18 MDO methodologies studied in the literature review available at the moment of this thesis, a short-listing process was performed in order to come up with a total of 10 MDO methodologies. These methodologies will be explained in greater detail in chapter 3 for the purpose of creating a solid background for the final recommendations for which this thesis is aimed, in order to provide a feasible set of recommendations for the MDO implementation into the CE process of DLR, the main criteria used to select this MDOs is as follows:

- Documented ability to cope with the number of variables and processes that are characteristic of the Space Vehicle Design.
- Successful applications in the aerospace industry as per the literature researched, for the past 3 decades.
- Mathematical applicability in regards of the problem formulation and solution vs the number of possible variables and domains to be optimized.
- Feasible implementation code for the MDO in regards of its solution algorithms.

It is important to note that a solid mathematical background is necessary to aim at fully understanding every MDO that will be explained here, thus a summarization of the general guides and knowledge is explained in Annex 1: Mathematical background hence the MDO explanations in this chapter aim at describing the mathematics just in the overall context of the architecture and not to the specific detail of the different mathematical optimization techniques.

Also an important remark is in regards of the language to which MDOs are addressed, throughout various papers available, as mentioned before, there is a lack of a standard way of labeling the different MDOs, for the purpose of this study each MDO is depicted as a methodology, thus analyzed in this way, different from what other authors acknowledge as architectures, techniques, etc. In the course of this thesis reference will be made as of MDO methodologies only.

Each Methodology will be addressed and explained mathematically from the point of view expressed in Balesdent et al. (2011) including the General visualization of the structure of the MDO method as a whole in the form of Diagrams, where all the elements of the MDO methodology are visible, these aids the easy understand of the way each MDO method works. For most of the analysis regarding implementation processes Martins and

Lambe (2013) is addressed with the explanation of the MDO in the form of a Extended Design Structure Matrix arrangement of inputs and outputs, since it is better for implementation processes, Martins and Lambe study is also used in this document regarding the code suggestion for implementation of the different MDO methods, and aided in the qualitative analysis and comparisons performed.

The resulting list of MDO methodologies that will be explained in detail is as follows:

Table 2. MDO methods short list; labeling as of Balesdent et al (2011)

MDO method		Authors
1	Multi disciplinary Feasible (MDF) or Nested Analysis and Design (NAND)	Balling and Sobieszczanski Sobieski,Cramer et al. (1994);
2	Individual Discipline Feasible (IDF) (optimizer based decomposition OBD) (SAND)	Cramer et al. (1994);
3	All at Once (AAO) (SSS: single SAND)	Balling and Sobieszczanski Sobieski,Cramer et al. (1994);
4	Collaborative Optimization (CO)	Braun and Kroo (1995);
5	Concurrent Subspace optimization (CSSO)	Sobieszczanski-Sobieski et al. (1988);
6	Bi-Level Integrated System Synthesis (BLISS)	Sobieszczanski-Sobieski et al. (1998);
7	BLISS-2000	Sobieszczanski-Sobieski et al. (2003);
8	Modified Collaborative Optimization (MCO)	Miguel and Murray (2000);
9	Analytical Target Cascading (ATC)	Michelena et al (1999);
10	Discipline Interaction Variable Elimination (DIVE)	Masmoudi and Parte (2006);

Prior to deep diving into the particularities of each of the MDO methodologies here explained, it is important to note that IDF and MDF are shortlisted not specifically for his applicability into the CE process but because they lay the foundations to easily understand the rest of MDO methodologies formulations, thus are a key element that needs to be understood. In the same line with the latter we found the Multidisciplinary Analysis also known as MDA, which is not a MDO itself but an important part of most of the formulations and in particular of those that derive from the MDF methodology in any degree, thus it will be addressed first.

2.1 Multidisciplinary Design Optimization General mathematical definition.

It is important before describing the different MDO methodologies, to define a clear framework, hence the importance to analyze the most General MDO mathematical formulation which in essence is nothing more than a numerical optimization problem subject to constraints that is described as follows.

Optimization problem summarization:

$$\text{Min } f(x,y,z)\text{, with respect to } x,y,z \quad * \tag{1}$$

$$\text{Subject to } g(x,y,z) \leq 0 \tag{2}$$

$$h(x,y,z) = 0 \tag{3}$$

$$\forall i, Ri\ (x_i, y_i, z_i) = 0\ * \tag{4}$$

$$\text{Where } \forall_i, \forall_{j \neq i}, y_i = \left\{c_{ji}\left(x_j, y_j, z_j\right)\right\}_j{}^* \tag{5}$$

(1) Is the objective function to be minimized (optimized).
(2) Is the equation representing inequality constraints.
(3) Is the equation representing equality constraints.
(4) Is the equation of Residuals between the different subdomains/disciplines.
(5) Is the equation that defines the couplings between subsystems “i” and “j”.

Where x, y, z are each a vector of variables which represents the state variables (x), coupling variables (y) and global Design Variables (z) subsequently.

It is important to note that the * in equation (1) is due to the fact that depending on the MDO methodology, the minimization could be performed to different combinations between the design variables and any other of the variables involved, depending on the concept of the methodology itself, but the concept is depicted correctly and holds for most of the MDO methodologies to be studied in this thesis.

For Equations (2) and (3), inequality and equality constraints need to be addressed and complied with while optimizing (minimizing) the objective function (1).
Equation (4) denotates the necessity of feasibility and convergence of the solution, which is to be kept to 0 in order to assure feasibility and convergence between the variables of the different systems.

It is also important to note that (4) could be expressed in different ways depending on the problem formulation of the MDO methodology used or study, and thus also is written here with an * stating just general formulation for the necessary introductory explanation purposes.

2.2 Multidisciplinary Analysis (MDA).

Multidisciplinary Analysis or MDA as it is most commonly addressed in MDO methodologies is the "process whereby an iterative scheme is applied to the disciplinary governing equations to establish equilibrium or multidisciplinary feasibility" Keane (2005), or more explicitly defined in the context of MDO, MDA is the element in the methodology application process that "aims to satisfy the coupling between subsystems" Balesdent et al. (2011), thus ensuring feasibility.

It is important to note that MDA is a process that needs to be performed, but the way in which is allocated in each MDO method deals a great significance and allows to adapt the optimization problem formulation to specific needs, or specific computational resources available.

Mathematically speaking MDA deals mostly with the satisfaction of the variables x_i such that the Residuals (4) are kept to 0 while still maintaining the coupling consistent. This means also convergence, but this sense of convergence relates in the case of the MDA to the values that allow the residual to be 0, thus the systems is compliant with feasibility and if also minimized through the objective function optimality.

Mathematically speaking a Residual is nothing more than a subtraction, in the sense analyzed here it is:

$$R = (observed\ value - estimated\ value) \tag{6}$$

Thus, if we want to find the variables such that:

$$Ri\ (x_i, y_i, z_i) = b \tag{7}$$

Given an approximation of xi, yi, zi to xo, yo, zo the residual now is:

$$b - Ro\ (x_0, y_0, z_0) \tag{8}$$

Loosely speaking the MDA process makes sure that the variables values of feasibility between disciplines are found such that in the calculation process we get b = 0 in equation (8) while still holding all other equations optimal (minimized) thus of course complying with the general expression of equation (4).

In other words, as noted in Balesdent et al.(2011) the MDA main aim is dealing with keeping equations (4) and (5) in check within the optimization process, thus when this is achieved we can talk a solution that went through this process is feasible for the whole spectrum of the disciplines analyzed by it. Depending on the core concept and more so the aim to which the MDO is set, the different MDO methodologies place or not the MDA in a specific part of the process so that the optimization process successfully complies with the methodology concept and aim.

It is also very important to notice that MDA is not a mandatory part of each MDO methodology and is not required in order to find optima, thus is an element that (as it will be seen in the description of the different methodologies) can or cannot be included in the overall formulation of a MDO problem.

2.3 MDO methodologies classification.

It is very important to have in mind that although labeling is a grey still not standardized area when it comes to MDOs methodologies in the general literature, there is a good level of consensus as regarding its classification, again labeling issues arise, i.e. Martins and Lambe use the distinction of monolithic and distributed systems when referring to MDOs classifications while Balesdent uses single level and multi-level to refer to the same two concepts of monolithic and distributed accordingly, but nonetheless the classification holds and is consistent independently of how it is labeled for most of the classifications in the available literature of the subject.

In deed classification of MDOs is a vast subject in itself, in a short overview, there are currently several ways to group and classify the different existent MDOs: by the type of algorithms used to solve the formulation of the problem, the type of mathematical optimization methods used (i.e. stochastic, Heuristic, gradient based), their characterizing roots from the most general methods (i.e. IDF or MDF derived), the type of constraints and design variables to be analyzed, by the way they divide the optimization problem into a single formulation or a multilevel formulation, etc.

For the purpose of this thesis the classification between multi-level and single level will be used as it is used by Balesdent et al. (2011), this type of classification aids in the understanding of each method, because it is easy to mentally relate to a single or multi level reference when looking at the diagrams that explain each of them, and also because thinking in the various disciplines and the way they relate in the process where the MDO is intended to be applied.

In order to correctly define and analyze the different MDO methodologies a simple but key element is also included in this thesis classification, which was first introduced by Cramer et al. (1994) but with higher graphical clarity in Martins and Lambe (2013). This element is the relation that the “newer” MDOs have with the two most mature methodologies which are IDF and MDF. Nonetheless an important difference with the view of Martin and Lambe principle in which most of the MDOs derive from an AAO methodology is also included in Fig.2, and it is that MDOs do not derive from a single mother method, but from a single formulation in the way of a general concept described in equations (1-5). Also the purpose of the classification performed in this thesis is particularly aimed at the overall goal of recommending a selection of MDOs that can be implemented in the DLR Concurrent Engineering process, thus Fig.2 must be taken into that context in order to render the comprehensible picture it is intended to, with its simplicity.

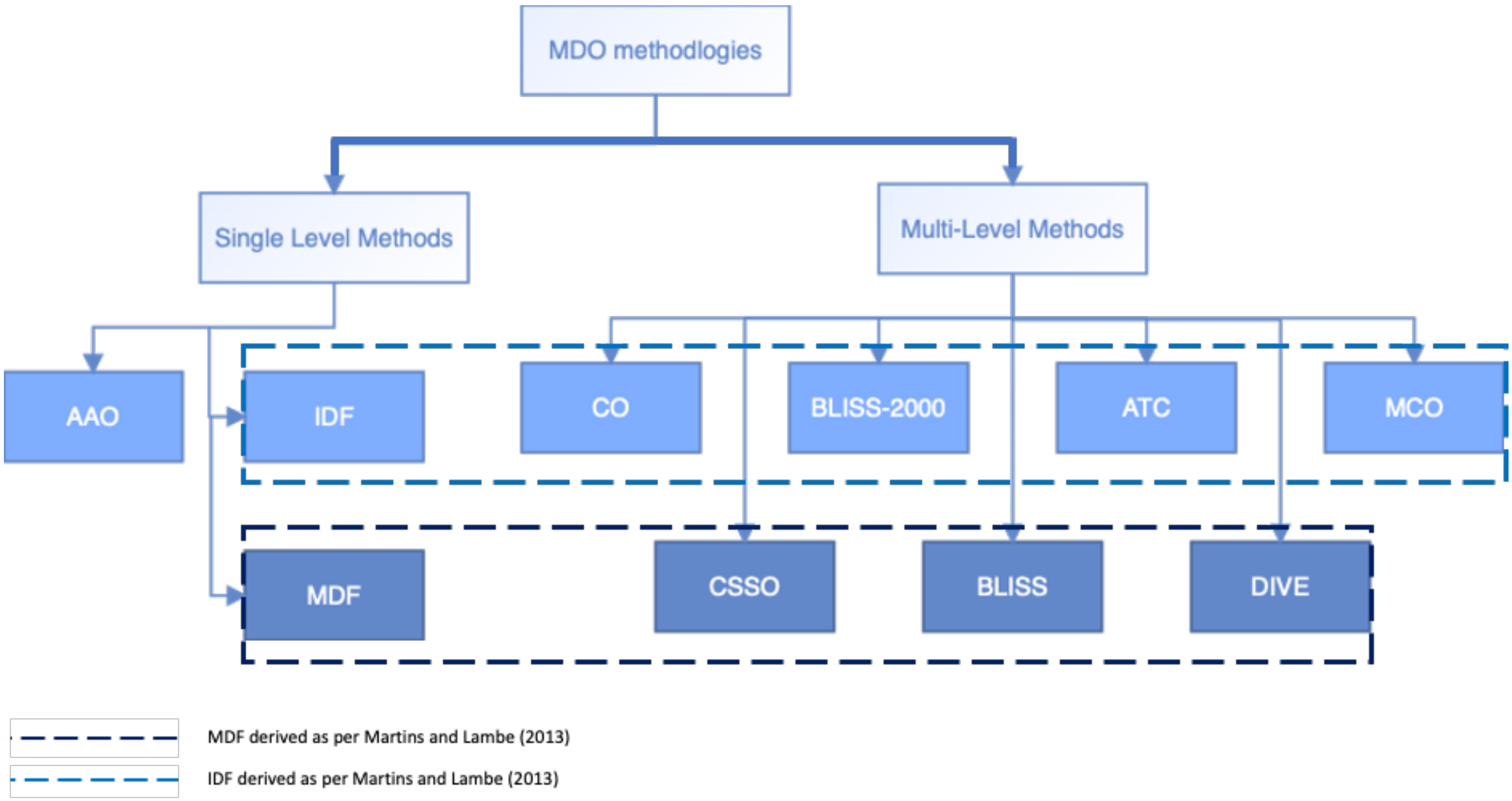

Figure 2. Selected MDO classification.

CHAPTER 3: MDO METHODOLOGIES DESCRIPTION

3.1 Multi Discipline Feasible (MDF).

The MDF methodology for MDO formulations is also addressed in the literature as "Nested Analysis and Design (NAND)", "Single NAND- NAND (SNN)", and "All in one", meaningful explanations of this method and its appliances as well as results are evaluated in Allison (2004), Balling and Sobieszczanski-Sobieski (1994), Cramer et al. (1994) among others. Along with IDF, AAO, CO, CSSO and BLISS up to some degree, it is one of the most tested and proven MDO methodologies currently in use and for which there is reliable data regarding its performance and implementation.

The MDF method has one of the straightest forward formulations, linking a MDA at system level with an overall single optimizer, which is in charge of the optimization of the objective function in relation to the Global Design Variables (DV). MDA is performed at each iteration thus allowing for feasibility check at each of the iterations performed, the DV are inputs to the MDA by the optimizer, then the MDA handles by a fixed point iteration method the optimization and feasibility of the state variables "x" through the equations (4)(5) and then returns this to the optimizer for an iterative calculation of the objective function and the constraints until convergence of the whole systems is achieved.

Since the MDA handles in each iteration run the satisfaction of equations regarding state variables and couplings for all related disciplines, it is said that each iteration produces a feasible solution, however it must not be taken out of the overall picture that since the constraint equations are handled by the system optimizer in a further iterative step, the term feasible might not be compliant with the general constraints and thus must not be misinterpreted, a better term for the design variables after each iterations would then be a set of "consistent design variables".

The most common mathematical formulation of MDF is listed as follows consistent with Balesdent et al. (2011):

$$\text{Min } f(Xc(z), y, z)\text{, w.r.t } z \quad (9)$$

$$\text{Subject to } g(Xc(z), y, z) \leq 0 \quad (10)$$

$$h(Xc(z), y, z) = 0 \quad (11)$$

As clearly noted, the optimization formulation of the common MDF problem looks simplified since the MDA is in charge of dealing with the formulation and consistency of the state variables and couplings between disciplines, which can be a strength or weakness in the implementation of a successful and efficient MDO problem formulation, depending of course on the complexity of the different disciplines, the number of coupling equations and variables.

The graphical interactions of this characteristics can be seen in figure 3. Which is taken from Balesdent et al. survey of MDO methodologies published in 2011.

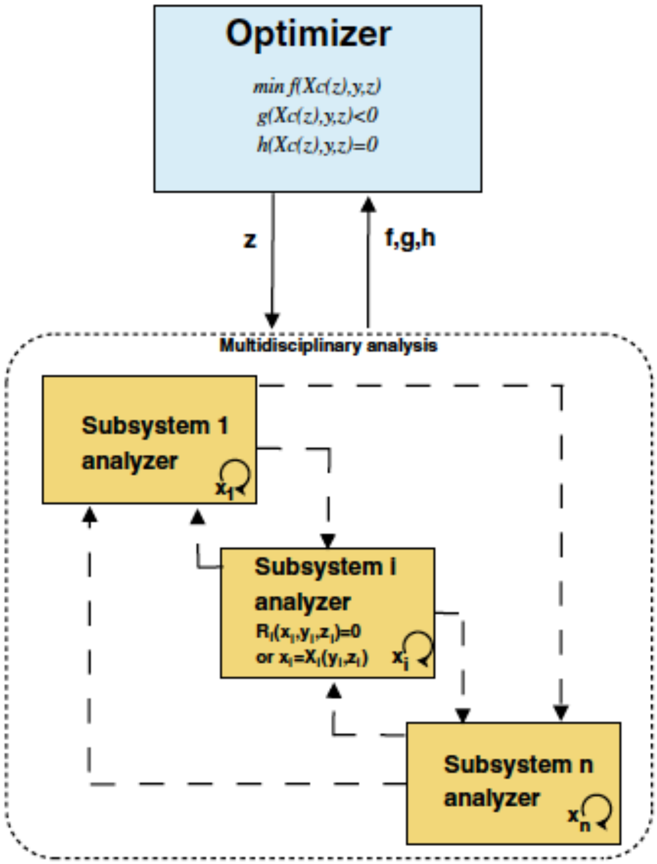

Figure 3. MDF method by Balesdent et al. (2011).

As depicted in figure 3. the state variables do not intervene in the optimization problem, but it is the MDA that returns an objective function calculation to be minimized in regard to the constraints by the system optimizer.

MDF is a very efficient method and has been effectively applied in the industry for optimization purposes, however it is important to take always into account that due to its simplicity in the formulation of the problem a great deal of problems arise when dealing with increasingly large number of variables or disciplines. Particularly one of the most common issues is the calculation costs due to an increasing need to have a robust MDA configuration, which has to be executed in each iteration, allowing for slower processing times when increasing the number of equations involved between different disciplines, such as is the case when Gradient based algorithms are employed in the MDA calculations. The system overall lacks flexibility in the sense that any changes in at least one of the disciplines requires a re-set and possible re-adjustment of the MDA.

Table 3. MDF Characteristics, Advantages and Drawbacks

MDO method	Comments/Short summary of Characteristics	Advantages	Drawbacks
Multi disciplinary Feasible (MDF) or Nested Analysis and Design (NAND)	- Single optimization at system level is used.	- Simple in general terms and concept.	- Since MDA is performed on each iteration the method doesn't profit from the couplings between disciplines to optimize
	- Uses MDA and iterates assuring feasibility on each iteration	- Feasible at each iteration.	- MDA performed at each iteration complicates the process when too many variables in play thus affecting convergence capabilities.
	- Uses Fixed Point Iteration (FPI)	- System decomposition is not mandatory.	- Poor modularity, due to the MDA performed at each iteration there is few to no room for parallelization of activities by decomposing into different modules.
	- All found solutions are feasible solutions, however the latter doesn't assure compliance with equality and inequality constraints for each Iteration just MDO Feasibility.	- Allows for feasible solutions even when there is no convergence of the optimizer.	
	Comments: The selection of this MDO depends on the availability of an MDA that is easily performed and have a quick convergent result as this is the major constraint for this method. As per Kodiyalam S (1998) Evaluation of methods for Multidisciplinary Design Optimization (MDO), phase 1. NASA/CR-1998-20716		

In order to provide a comprehensive list of drawbacks and advantages of MDF, table 3 presents a summarized overview taking into account the context of the CE process of DLR.

As it will be seen later in chapter 4 where the CE process is described in detail, each space vehicle project is very different from each other, and depending on the scalability and size of the problem to be formulated or the specific application in conjunction with other MDO methodology MDF can still be put to a good use, and thus is one of the shortlisted MDOs as a result of this thesis study.

3.2 Individual Discipline Feasible (IDF)

The Individual Discipline Feasible method, also known in the literature as “Optimizer Based Decomposition (OBD)”, “Single-SAND-NAND (SSN)” is a MDO method that as MDF uses a centralized optimizer but introduces the concept of dividing the disciplines in subsystems, all linked together by coupling variables which are handled at system level by the common optimizer, thus opposite to MDF allowing for individual feasibility in the state equations per subsystems but system feasibility only at convergence (Optimizer deals with the couplings in its optimization process), this latter important concept is why this methodology is called “Individual Discipline Feasible”.

It is suitable then (as presented in Balesdent et al. (2011) and Bil (2015)) when explaining the different MDO methodologies to follow a logical order and explaining IDF, just after MDF has been clarified, this is essentially because IDF is a MDO formulation that provides a way to avoid performing an MDA in its complete form in the MDO methodology.

The most common mathematical formulation of IDF is listed as follows consistent with Balesdent et al (2011):

$$\text{Min } f(X(y_i, z), y, z), \text{ w.r.t } y, z \qquad (12)$$

$$\text{Subject to } g(X(y_i, z), y, z) \leq 0 \qquad (13)$$

$$h(X(y_i, z), y, z) = 0 \qquad (14)$$

$$\forall i, j \neq i, y_i = \{c_{ji}(X_j(y_j, z_j,) y_j, z_j)\}_j \qquad (15)$$

In the IDF mathematical formulation the coupling variables are treated and included in the system optimization, thus state variables are now put in function of the coupling variables and the global DV (Design Variables) thus the system optimizer makes no distinction between DV and coupling variables in the optimization process, but evaluates the state variables already in function of the coupling variables (and global Design Variables), in order to perform this, a vector of copies of the coupling variables is used, and the subsystem analyzer deals with his own copy of the coupling variable “y_i” in the calculation of his state variables, all this is kept consistent by the evaluation of Residuals (4) at each subsystem but not at the system level, thus returned to the optimizer until convergence assures optimal and feasible for the system as a whole.

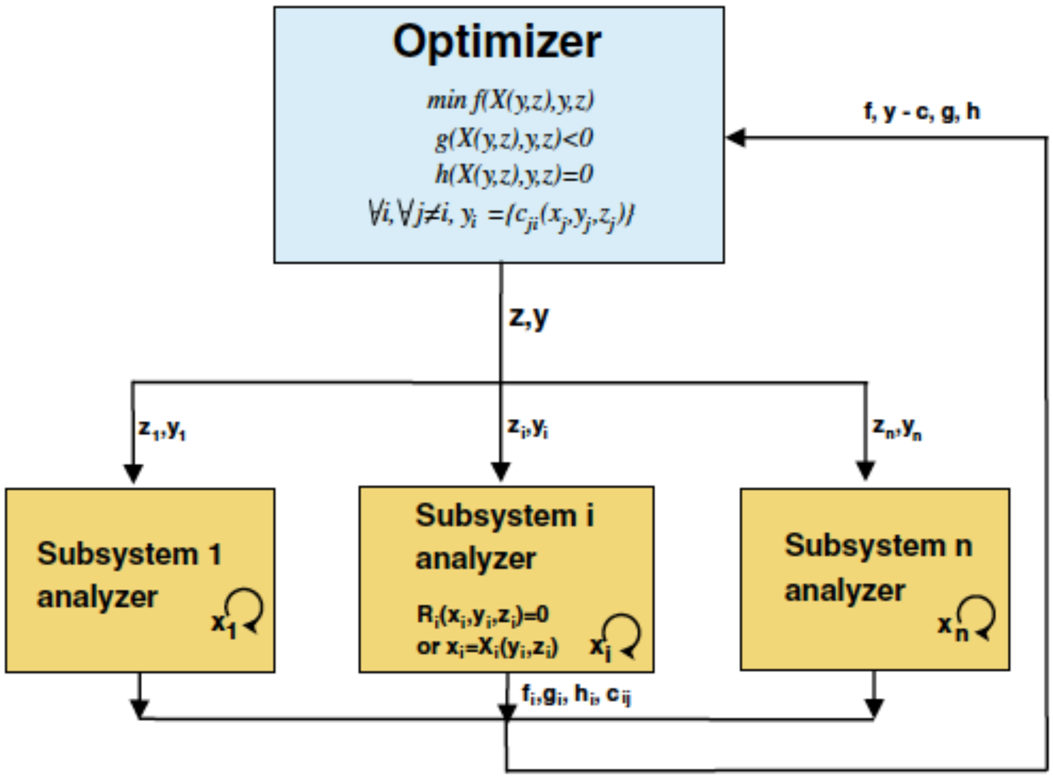

Figure 4. IDF methodology as per Balesdent et al. (2011).

The IDF MDO methodology implementation allows for the discipline analysis to be performed in parallel between disciplines, since feasibility, consistency and satisfaction of couplings is achieved at the optimization process at system level, and not per discipline, being this its main advantage is also depending on the size of the problem to be solved its main drawback, as too great a number of disciplines with tight couplings between them poses a problem in the formulation of the IDF methodology and deeply affects the convergence time of the optimization process. The latter is a matter of computational power, and thus could be addressed but this in most of the cases means also an increase in computational cost, needed to improve solution times.

In summary IDF represents an advantage against MDF that specifically aims at a network implementation, that improves efficiency in calculations compared to MDF (at least theoretically since there are comparisons in the literature with various results), but might if the MDO problem to be solved is too large, be equally hard to formulate or too expensive to implement, computational solution wise.

It is also very important to note that when the IDF methodology doesn't achieve convergence, the results at this stage do not assure a valid configuration.

Table 4. is a brief summary of the main particularities of IDF methodology and its advantages and drawback as found in the literature and analyzed in this thesis.

Table 4. IDF Characteristics, Advantages and Drawbacks.

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
Individual Discipline Feasible (IDF) (optimizer-based decomposition OBD) (SAND)	- Single optimization at system level is used.	- Allows for improved efficiency in regard to MDF due to the availability of parallelization.	The assurance of results and gains in speed can be expected only for problems with relatively small amount of coupling variables, depends on convergence of the whole optimization model for feasibility of the solution.
	- The optimizer is responsible for coordination between subsystems thru coupling variables.	- Calculation times are reduced due to network implementation with all subsystems.	
	- The minimization of the objective function is performed in regard to the global and coupling variables thus coupling consistency is achieved only at total convergence and not through each iteration	- Allows for individuality, freedom in optimizing each domain without checking for overall feasibility.	

3.3 All At Once (AAO).

The AAO methodology also known as “Single SAND-SAND (SSS)” is commonly known in the literature as the most elemental method regarding the MDO methodologies, this is strongly depicted in Martins and Lambe (2013), where they based their survey study of the different “MDO architectures” on the concept of adding, removing or reconstructing AAO in order to derive the other MDO methodologies.

The All At Once methodology is basically a very broad and general mathematical formulation of the optimization problem, that handles the control of the overall optimization to a centralized optimizer. This centralized optimizer is in charge of the minimization of the objective function in regards of the global DV, coupling variables and state variables.

At Subsystem level (disciplines) the formulation focus is on calculating the residuals, without necessarily dealing with the compliance of equation (4) at this level, but transmitting this calculation to the centralized system optimizer, everything performed at the same time, hence from there the name of the method.

The most common mathematical formulation of AAO is listed as follows, consistent with Balesdent et al (2011):

$$\text{Min } f(x, y, z), \text{ with respect to } x, y, z \tag{16}$$

$$g(x, y, z) \leq 0 \tag{17}$$

$$h(x, y, z) = 0 \tag{18}$$

Subject to

$$\forall i, Ri\ (x_i, y_i, z_i) = 0 \tag{19}$$

$$\forall i, \forall j \neq i, y_i = \{c_{ji}(x_j, y_j, z_j)\}j \tag{20}$$

AAO methodology concentrates the MDO in its centralized optimizer, thus the level of centralization has more incidence in the performance of the method as a whole than in IDF and MDF. Also, since the subsystems are only responsible for the calculation of the Residuals but not its satisfaction with equation (19), these will be equal to 0 only at convergence of the whole system to the optimum. This means that neither multidisciplinary nor individual disciplinary feasibilities can be achieved, if the process has not yet converged neither found an optimum.

It is clearly based on the mathematical description of this methods that its use in launch vehicle design is pretty much unfeasible, because most of launch vehicle design projects are too large in scale to be handle to AAO, however the decision was made to short list this method due to its simplicity in the formulation and applicability of the overall problem solving methodology into specific domain, thus AAO could be used in the CE design process of DLR not as the complete solution of the MDO implementation but perhaps as a part of these greater MDO solution. In chapter 5, where the recommendation to the CE process of DLR is explained, AAO is of value in regards of the recommendation itself.

An important concept needs to be introduced as well to fully understand the way in which the AAO methodology works when solving a MDO problem: the use of Disciplinary Evaluators, this name is used in a very versatile way by Balesdent et al. (2011) and is very useful when looking at the way AAO mathematical formulation works in regards of the centralized optimizer and the different disciplines, the definition is as follows: The disciplinary evaluation consist in calculating the value of the residual equation (7) from x_i, y_i, z_i In this scheme, the equation (4) is not solved. Furthermore, the state variables represented by the vector X are not handled in the subsystem but are considered as inputs in the same way as z and y.

Once this is understood the general AAO methodology scheme can be appreciated in its full context and logic in figure 5.

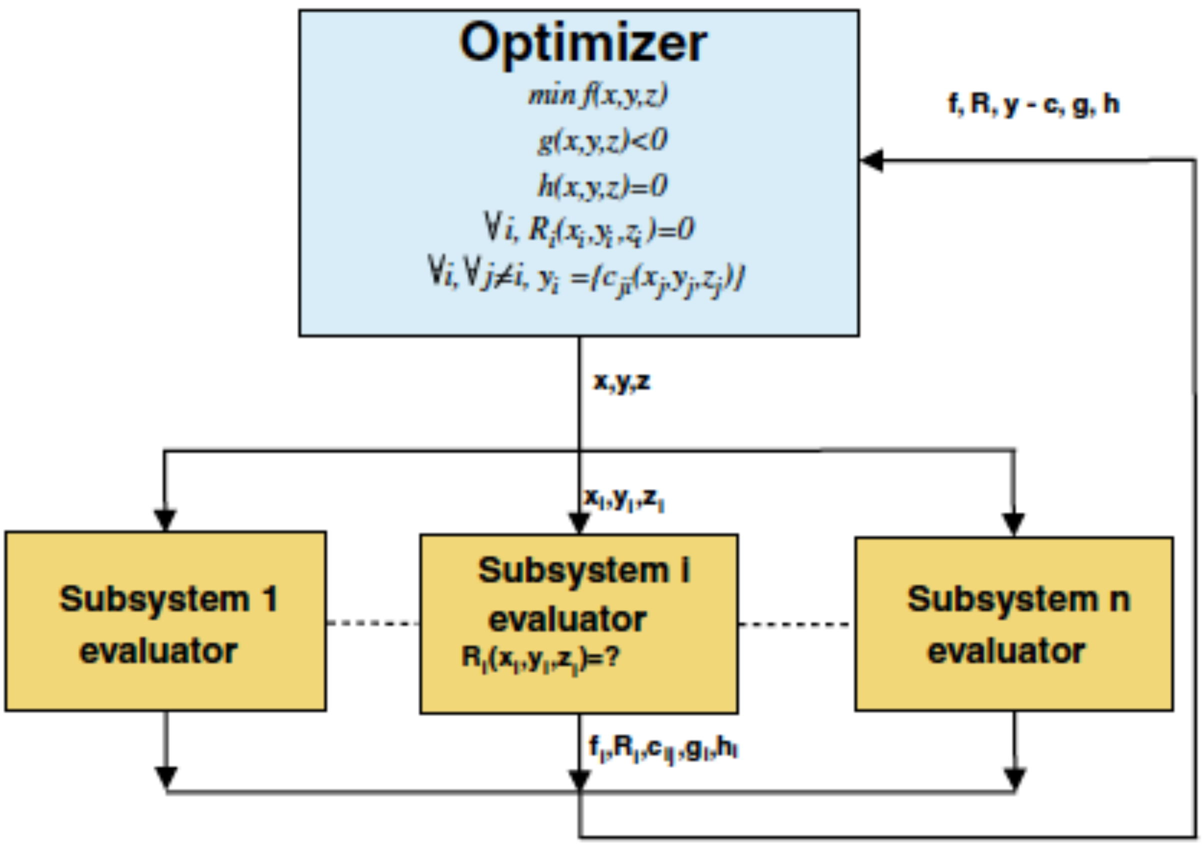

Figure 5. AAO methodology as per Balesdent et al. (2011).

Table 5. AAO Characteristics, Advantages and Drawbacks

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
All at Once (AAO) (SSS: single SAND)	-Single optimization at system level is used.	-Simple practical implementation and application.	- Due to its implicit simplicity when problems such as vehicle launch are modeled the number of variables make it inapplicable due to the complexities arisen from the multiple complex systems that need to be handled in parallel.
	-Solves simultaneously the optimization problem and the state equations.	-Simple functioning in the iteration process and conceptually clean to understand.	
	- There is only consistency with solution at total convergence of the overall system.		
	- Uses disciplinary evaluators.		

3.4 Collaborative Optimization (CO).

The Collaborative Optimization MDO methodology focusses its formulation on two main purposes, one is to allow complete independence of each discipline optimization subproblems, and two, create a simple data sharing protocol that allows for interdisciplinary compatibility, in order to achieve these CO relies on a two level optimization process, having an independent optimizer for each discipline that is in charge of its local design variables, local constraints satisfaction and has no external incidence by the other disciplines, then a system level optimizer deals with the coordination and optimization of the whole process and objective function. Thus CO as its name states it, relies on a sub level of optimizers that deal with copies of the main variables involved in the optimization process as a whole, work on optimizing its independent formulations and then a major optimizer perform the coordination in other to fit these collaborative optimizations into a single result, while at the same time performs the minimization of the objective function to find the optima of all the collaborations put together.

The main idea of CO is to allow independence in the optimization of each problem through liberties in the mathematical formulation of each sub optimizer. This allows also for the intervention of experts on each discipline, without having to adhere to other disciplines optimization in their own discipline but just focus on individual optimization, while delegating the coordination and collaboration to the main optimizer, which has to combine inputs from all disciplines in order to come up with a feasible, consistent optimum that englobes the whole system.

CO mathematical formulation as per Balesdent et al. (2011) is as follows:

System level:

Min $f(y, z)$, with respect to y, z (21)

Subject to $$\forall i, Ji^{*}\ (z^{*}, z, y_i, c_i(y_i, z_i{}^{*})) = 0 \tag{22}$$

Ji^{*}: Optimized objective function of the ith subsystem.
z^{*}: Local copies of the global design variables.

Sub-System level:

For the ith subsystem/discipline,

$$\text{Min } Ji\ (z_i, z_i{}^{*}, y_i, c_i(y_i, z_i{}^{*})) = \|z_i{}^{*} - z_i\|_2^2 + \left\|y_{ij} - c_{ij}(y_i, z_i{}^{*})\right\|_2^2 \tag{23}$$

w.r.t. $z_i{}^{*}$

subject to
$$g_i(y_i, z_i{}^{*}) \leq 0 \tag{24}$$
$$h_i(y_i, z_i{}^{*}) = 0 \tag{25}$$

For which y_{ij} are the coupling variables of ith subsystem/discipline to the jth one.

There is a second formulation of the CO MDO methodology by Alexandrov and Lewis (1999) which consist in replacing the system level constraint vector by a set of two equations that are both then made equal to 0 for root finding and solution, the formulation used in real practice depends on the specifics of the MDO problem to be handled, for the purpose of this thesis it is important just to acknowledge its existence.

In figure 6 it is seeing graphically how CO works, and the interactions between the system optimizer and the local optimizers of each discipline. The system optimizer feeds the global DV (Design Variables) and the coupling variables into the local Optimizers. Each local optimizer creates the copies necessary for its own sublevel optimization and returns the results in the form of equation 22, for which another iteration is performed by the system optimizer (this step is known as post optimality analysis) until convergence is achieved for the whole system.

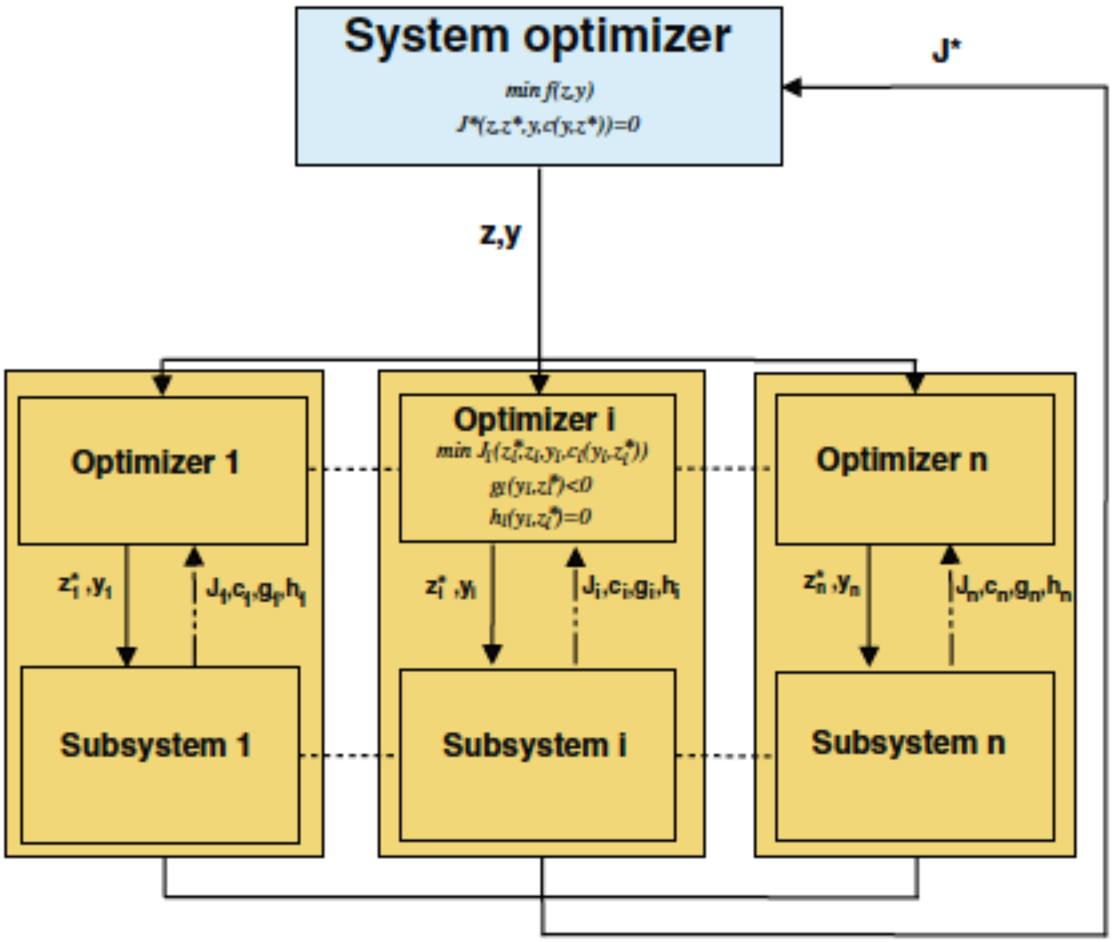

Figure 6. CO methodology as per Balesdent et al. (2011).

CO is a powerful breach in MDO formulations, and represent a new way of not just structuring the problem but also a way to introduce flexibility in the way of an improved modularity, thus if a new discipline is needed to be included in the problem formulations, due to the way it works this can be done without much effort by just adding another module in the second level where the local optimizers are located, more so, local optimizers can be customized to the specific needs of the disciplines or domains, and to the experts working with them allowing for specific codes at the second level of the optimization process that greatly eases calculation times. The Collaborative Optimization MDO method however has clear weaknesses, particularly in the mathematical formulation of which is formed, these mathematical weaknesses derive from the number of inequalities vs the number of variables that needs to be dealt with, since inequality constraints appear per discipline and are greater in quantity than variables. The problem when too large becomes often infeasible, or at least shows a very poor performance in practice, as described by Alexandrov et al. (2002) and DeMiguel et al. (2000). Table 6. Shows a summarized detail of the draw backs and advantages of this method.

Table 6. CO Characteristics, Advantages and Drawbacks.

MDO method	**Comments / Short summary of Characteristics**	**Advantages**	**Drawbacks**
Collaborative Optimization (CO)	- Two level optimization method. - Global variables are copied and optimized at subsystem level complying with state problems, and then transmitted to the overall optimizers that coordinates the Global optimum result with the rest of subsystems.	- Improved modularity gained by the level of independence of each subsystem, thus allowing the flexibility to add or remove disciplines without major alterations to the whole MDO code.	- Due to a centralized global optimizer is used and this is responsible for dealing with the couplings between systems, large and complex constructions with large number of domains and thus variables, create instabilities in the convergence and affect efficiency of the method.
	- Works solving at the subsystem level without interference from other subsystems, and having an overall global optimizer coordinating the optimization of the Global Objective function while keeping the sub-levels optimized.	- Independent optimization mathematics as better suitable for each sub level optimizer can be implemented.	
	- Coupling variables are introduced at subsystem level to deal with satisfaction of variables between subsystems, thus each subsystem satisfies his own constrains and try to match target values on coupling functions that are needed by other disciplines in the evaluation of their constrains.	- Response surfaces methods can be used in order to improve calculation and convergence speeds.	

3.5 Concurrent SubSpace Optimization (CSSO).

The CSSO MDO methodology is one of the first MDO methodologies that explored the utilization of a multi-level optimization method, it was first developed in 1988 but its evolution from the early formulations by Sobieszczanski–Sobieski (1988) are evident. For the purpose of this thesis the inclusion of CSSO into the selected shortlisted methods for the CE process of DLR is mainly due to the formulations of the method by Tappeta et al. (2002) and Zhang et al. (2008), these formulations include major improvements to the method by the inclusion of surrogate models into the general formulation as well as the use of approximation models.

In synthesis, CSSO is an iterative method based on a decomposition strategy that places sub level optimizers into each of the disciplines in the MDO problem. Each sub level optimizer minimizes the system objective function subject to its own constraints and the constraints of the other disciplines concurrently. This latter is performed by the introduction of the so called global shared design variables that are handled by the sub level optimizer, with a system level coordinator-optimizer on top handling the overall process.

CSSO when used in its original formulation might perform poorly in comparison with newer MDO methodologies as researched in Perez et al. (2004), Yi et al. (2008) and Tedford and Martins (2010), but it is the use of surrogate and approximation models that has given CSSO good results in recent years and thus stands out as a feasible method for the CE process of DLR, subject of course to the scale of the problem to be formulated. Nonetheless the CSSO concept is an important one in a theoretical way, since it allows the introduction to other MDO methodologies that work in a similar way but with conceptual improvements such as BLISS or BLISS-2000.

There are different mathematical formulations for the CSSO method however in order to keep a certain level of standardization through this thesis, we adhere to the one presented by Balesdent et al. (2011).

System Level:

Min $f(\tilde{y}, z)$, with respect to z (26)

Subject to,

$$g(\tilde{y}, z) \leq 0 \, * \quad (27)$$

$$h(\tilde{y}, z) = 0 \quad (28)$$

*for which $\tilde{y}$ are the approximations of the coupling variables.

Sub level Optimizer:

Min $f\left(\tilde{y}_{ji}, z_{sh}, \bar{z}_i\right), j \neq i$, w.r.t. $\bar{z}_i$ (29)

Subject to,

$$g_i\left(\tilde{y}_{ji}, z_{sh}, \bar{z}_i\right) \leq 0 \quad (30)$$

$$h_i\left(\tilde{y}_{ji}, z_{sh}, \bar{z}_i\right) = 0 \quad (31)$$

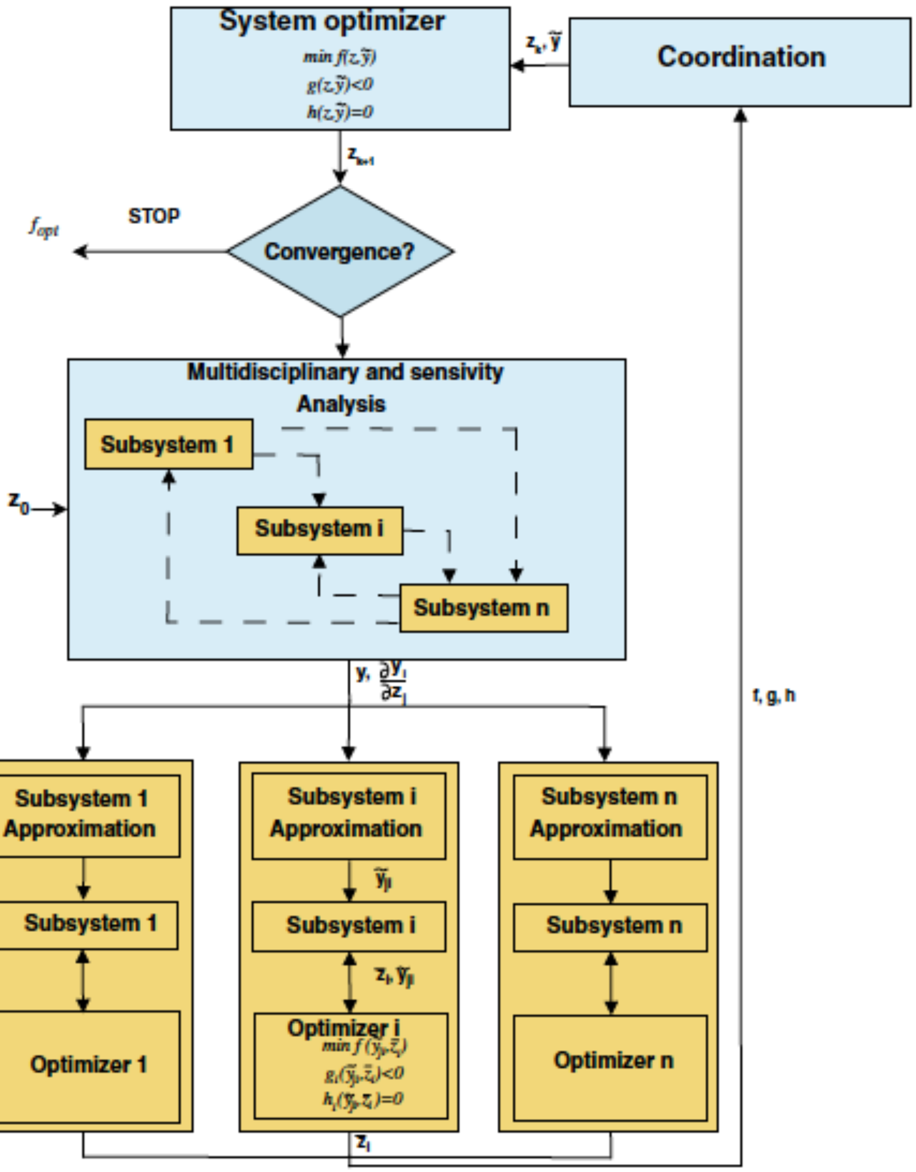

Figure 7. CSSO methodology as per Balesdent et al. (2011)

Table 7. CSSO Characteristics, Advantages and Drawbacks

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
Concurrent SubSpace optimization (CSSO)	- CO Philosophy is the core of this method with the additional concept that each discipline attempts to satisfy its own constraints as well to approximations to the constraints of the other disciplines (domains).	- When integrated with Pareto optimality concept it can be used to solve multi-objective large-scale problems with a CSSO-based method.	- Efficiency of the method relies strongly on the approximate models of the coupling variables thus when this are nonexistent and need to be created, they will highly influence the results as well as pose extra work.
	- Shared design variables are considered as constants during the concurrent optimization at the subsystem level and then coordinated at the System Level.	- Optimization time is reduced due to the approximations made and the way the linearized models create a database which is used by the local optimizers in order to optimize the objectives and satisfy the constraints.	- In summary for small systems with relatively easy ways to formulate approximation models the CSSO is a good option, however these is not the case for CE in Vehicle launch, in most of the cases.

It is very important to note that the efficiency of CSSO highly depends on the approximate models of the coupling variables, and it is the impression of this author due to the information available on the CE process of DLR, that this is not a common scenario for most of the space vehicle design studies, not because there is inability to generate these approximation models but because of the complexity that this represents and the time and resources that could possibly need.

Nonetheless, CSSO remains a powerful MDO that, used wisely when applicable, could be a very good solution and fitting method for a CE process.

3.6 Bi-Level Integrated System Synthesis (BLISS) and BLISS-2000.

The Bi-Level Integrated System Synthesis known as BLISS is one of the most recent MDO methodologies that had been developed (1998-2003). As CSSO it has a former formulation that is known under BLISS-2000 which uses response surfaces and approximation models in its structure and formulation to aid its overall performance in regards of robustness, feasibility and cost. Although Both methodologies share the same core concept (they both are multi level MDOs with focus in the independence of the different disciplines), and hence the name, they differ greatly in a key factor, BLISS relies heavily in a MDA process at system level and by a sensitivity analysis, while BLISS-2000 does it in the Response surfaces at the subsystem level, thus BLISS is closest to a MDF formulation and BLISS-2000 to an IDF formulation.

In essence BLISS is a multi level iterative method, whose main structure is composed by a system optimizer and a set of multilevel optimizers. Each discipline is optimized in regards of the variations of the local state variables while holding the global Design Variables constant and performing the minimization of the disciplinary objective function under local constraints, then these results serve as input into the system optimizer which now does the opposite leaving the state variables constant and optimizing the global Design Variables, that now will serve as input for the next iterative run, however prior to that an MDA and sensitivity analysis for the whole system is performed. Note that in order to avoid the new set of Design variables to move far away from the desired design point, thus making the approximations too inaccurate, the sensitivity analysis is performed prior to optimizing at subsystem level. The method used to perform the latter can be through the use of Global Sensitivity Equations (GSE) or local Lagrange multipliers, the selection used depends on the level of information available for each set of disciplines and will render what is known in the literature as BLISS A or BLISS B.

BLISS mathematical formulation as per Balesdent et al. (2011) is as follows:

At the kth iteration,

Given f_k, z_{shk}

$$\text{Min } f_k + \frac{\partial f}{\partial z_{sh}} \Delta z_{sh} \quad \text{w.r.t } \Delta z_{sh} \tag{32}$$

For the ith subsystem:

Given $z_{sh}, \bar{z}_i, y_i$

$$\text{Min } \frac{\partial f}{\partial \bar{z}_i} \Delta \bar{z}_i \quad \text{w.r.t } \Delta \bar{z}_i \tag{33}$$

Subject to,

$$g(\bar{z}_i, z_{sh}, y_i) \leq 0 \tag{34}$$

$$h(\bar{z}_i, z_{sh}, y_i) = 0 \tag{35}$$

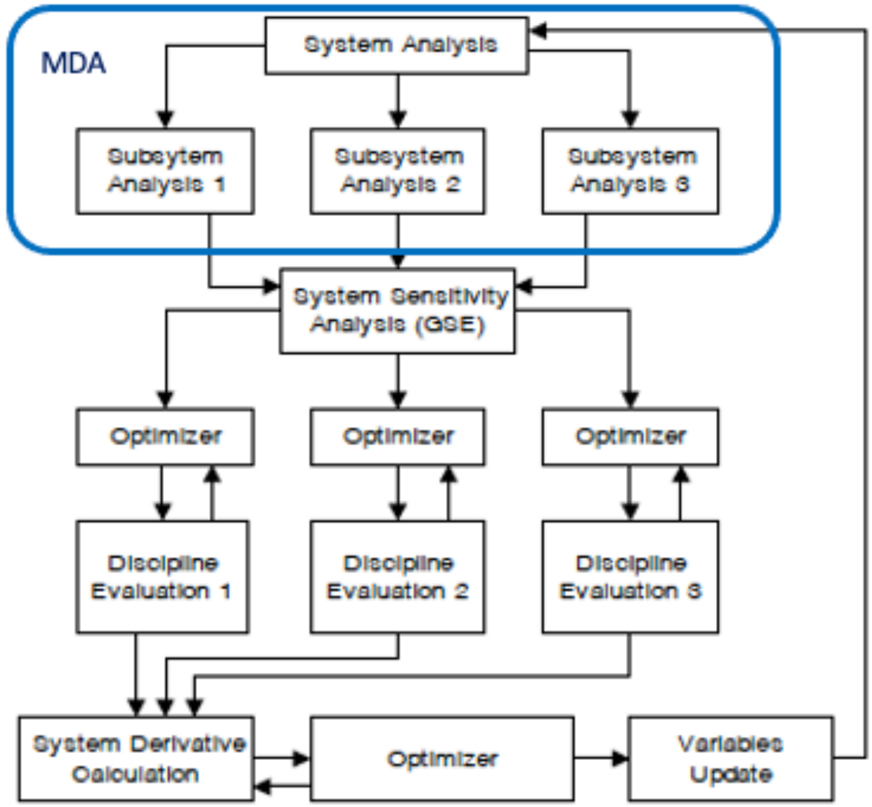

Figure 8. BLISS methodology as per Perez et al. (2004) with modifications.

An example of the structure of BLISS in fig.8 coming from Perez et al. (2004) is used since it clearly depicts the flow of the methodology and provides a useful insight regarding two key aspects: one, the system analysis is performed at a system level thus even though there is freedom in the individual optimization process of each discipline, the feasibility is kept together as a whole, resting individual feasibility, and two, the same is true as of the sensitivity analysis. These two key elements are clearly visualized in this figure and need to be understood in order to properly review the BLISS-2000 method.

Overall the BLISS MDO methodology is a well-designed well researched method, which is highly enhanced in terms of performance and reliability, when the expertise knowledge of the optima search space is well known and included in the formulation, thus the presence of user designed variable bounds helps the convergence if these bonds are properly selected. This is the case for some CE disciplines in which the major part of the optimum search space is already known, however it several might not be applicable for all of the disciplines.

Table 8. BLISS Characteristics, Advantages and Drawbacks.

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
Bi-Level Integrated System Synthesis (BLISS)	- Optimization is performed by dividing the overall optimization problem into sub-optimizations at the sub-levels.	- Due to the way the optimization problem is handled in a two stage multilevel way, the usage of specific optimization tools for each subsystem is possible.	- Due to the Gradient based methodology the method becomes hard to converge if the search space is rather too large or poorly defined.
	- Coordinated optimization at the system level works by fixing the joint variables and global design variables while optimizing each subsystem local variables thru the same objective function, then extrapolation of each subdomain optimum is performed as a function of the global and joint variables based on sensitivity analysis and a global optimum is searched.	- MDA is performed allowing each iteration to be fully feasible even when not global optimal.	- Designed to handle small number of global design variables.
	- Process above repeats until convergence is achieved for the whole system.		- The MDA process performed depending on the size of the problem to be solve, adds complexity and computation time as well as computational resources.
	- MDA is applied at a system level to assure feasibility.		

The BLISS-2000 methodology is characterized and different from its predecessor (BLISS) in the sense that does not require an MDA to be performed in order to restore feasibility of the design. BLISS-2000 uses instead, coupling variable copies to enforce consistency while searching the optimum, more so a radical change and improvement is the adaptation of the response surfaces or surrogate models to be used per discipline thus allowing its customization to fit the local optimization of each discipline, all along the optimization process the response surfaces can be improved by the addition or removal of points or data which aids in defining and delimitating the optima search space.

BLISS-2000 also adds to the mathematical formulation the use of weight coefficients, attached to the discipline's states, which provides the experts with a useful tool to measure and control the state variables preferences. These coefficients are to be selected in the best of the cases, based on the structure of the global objective, to allow the discipline subproblems to converge faster.

BLISS-2000 mathematical formulation as per Balesdent et al. (2011) is as follows:

At the system level,

$$\min \; f(z, y, w) = \tilde{o}_j \;\text{ w.r.t }\; z, y, w \tag{36}$$

$$\text{Subject to} \quad y_i = \left\{\tilde{c}_{ji}(y_i, z_i)\right\}_j \;\forall_i, \forall_{j \neq i}, \tag{37}$$

For the ith subsystem:

$$\text{Min} \sum_k w_{ik} * o_{ik} \;\text{ w.r.t }\; \bar{z}_i \tag{38}$$

Subject to,

$$g_i(y_i, \bar{z}_i) \leq 0 \tag{39}$$

$$h_i(y_i, \bar{z}_i) = 0 \tag{40}$$

The BLISS-2000 method has several advantages compared to BLISS and other MDO formulations. In their literature survey of "architectures" Martins and Lambe (2013) list from their point of view, what the most exact definition of advantages is, as follows:

1. The solution is easier to understand and reduces the obstacles in implementation.
2. The mathematical formulation of BLISS-2000 allows for the selection of appropriate weight coefficients to accurately emulate the influence of the coupling variables and improve the convergence properties suited to the process aim.
3. By using surrogate or response surfaces by discipline instead of for the whole system, the calculations can be run in parallel with minimum communication between disciplines and with a high level of precision for each discipline.

From the literature review and as of the context of Space Vehicle Design, BLISS-2000 is one of the most promising methods. It is important to remark that there are benchmarking reviews for the Space Vehicle Design such as Brown and Olds (2006), where BLISS-2000 tends to outperform the compared single level methodologies while remaining cost efficient. It is noted too that BLISS and BLISS-2000 render excellent results when the MDO problem is correctly decomposed and there is a clear delimitation of the optimum search area, hence the method is highly dependent on the quality of the response surfaces or metamodels used.

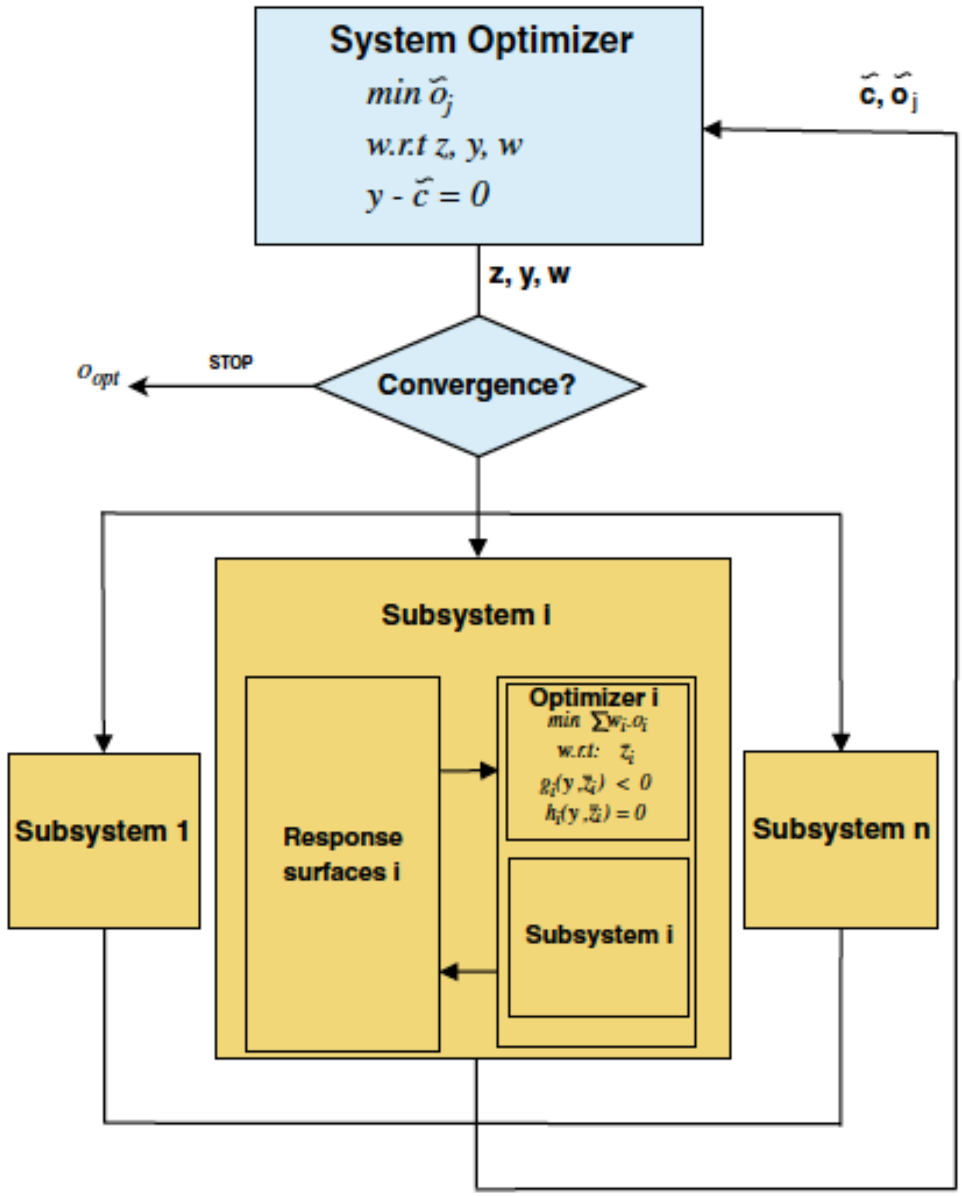

Figure 9. BLISS-2000 methodology as per Balesdent et al. (2011) with modifications.

While most of the research benchmarking for BLISS show results indicating the method to be far too expensive when in comparison with other similar bi-level decomposing methods, there is indeed a clear advantage when comparing these same methods with BLISS-2000. A key element is the reformulation that provides parallelism in the calculations and adaptability of the model to the global objective function by the weighting factors.

Table 9. BLISS-2000 Characteristics, Advantages and Drawbacks.

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
BLISS-2000	- Uses the same concept as in the original BLISS but adds a system of weighting factors to structure the set of disciplinary (sub system level) outputs.	- Separates the system level optimization and the subsystem level optimizations allowing for the usage of specific system optimization tools at subsystem level that can be targeted to enhance optimization of certain subsystems.	-Due to the Gradient based methodology the method becomes hard to converge if the search space is rather too large or poorly defined.
	- Groups thru these weighting factors the state variables and coupling variables, thus the optimization at the subsystem level consist now at optimizing the weighted sum of their outputs.	- Due to the structure of decomposition, the method allows for large human intervention on the subsystem level and proper theoretical DoE that gives robustness when validating the response surfaces models it needs to correctly be implemented.	- The BLISS 2000 is also highly dependent on the quality of the response surfaces which approximate the solutions of the optimization subproblems.
	- The Local optimizers are aided by sets of response surfaces which approximate the optimized outputs per subsystem, the response surfaces can be manipulated during the process of optimization.		- The method is in principle designed to handle a small number of global design variables.
	- Gradient based method mostly.		
	- The MDA process as well as Sensitivity analysis is replaced at the system level from the normal BLISS to a Response surface setup on each Subsystem.		

3.7 Modified Collaborative Optimization (MCO).

The modified collaborative optimization method is, as its name calls it, a revision of the CO method. It provides a mathematical formulation which gains mathematical rigor for the satisfaction of successful algorithm implementations. It does this by the relaxation of the troublesome constraints in equations (23-25), implementing a penalty system with an exact penalty function (fixed penalty parameter values and elastic variables to preserve the smoothness of the problem).

MCO mathematical formulation as per Balesdent et al. (2011) is as follows:
System level:

$$\text{Min } f(y,z) + w\sum_{i=1}^{N} Ji^*(z,y), \text{ with respect to } z, y \quad (41)$$

Ji^*: Optimized objective function of the ith subsystem.

Sub-System level:

For the ith subsystem/discipline,

$$\text{Min } Ji = \sum(s_i + t_i) \quad (42)$$
$$\text{w.r.t. } z_i^*, s_i = \{z_{si}, c_{si}\}, t_i = \{z_{ti}, c_{ti}\}, r_i$$

$$hi(z_i^*) = 0 \quad (43)$$
$$gi(z_i^*) + r_i = 0 \quad (44)$$

$$\text{subject to } z_i^* + z_{si} - z_{ti} = z_i \quad (45)$$
$$c_{ij} + c_{si} - c_{ti} = y_i \quad (46)$$
$$s_i, t_i, r_i \geq 0 \quad (47)$$

where:

r_i slack variables added to transform the inequality constraint g ≤ 0 in an equality one.

s_i, t_i are the elastic variables ($s_i, t_i = 0$ at convergence)

w the penalty coefficient (weight)

Table 10. MCO Characteristics, Advantages and Drawbacks.

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
Modified Collaborative Optimization (MCO)	- Same architecture as of CO but with enhancement on the penalty function into an exact form, thus allowing more stability in the process of convergence.	- A greater level of stability is achieved compared to CO by the addition of mathematical formulation in the form of elastic variables and penalty functions.	- The formulation of an overall optimization problem rises in complexity at the design and adjustment stage without necessarily improving the convergence assurance.
	- Replaces the quadratic local objective form (local optimizer) by a IDF form by adding elastic variables.		- Even when improving stability to converge, when dealing with a large number of variables, the construction and formulation of the problem poses a challenge that highly increase cost.
	- Equality constraints are also treated with a penalty form.		

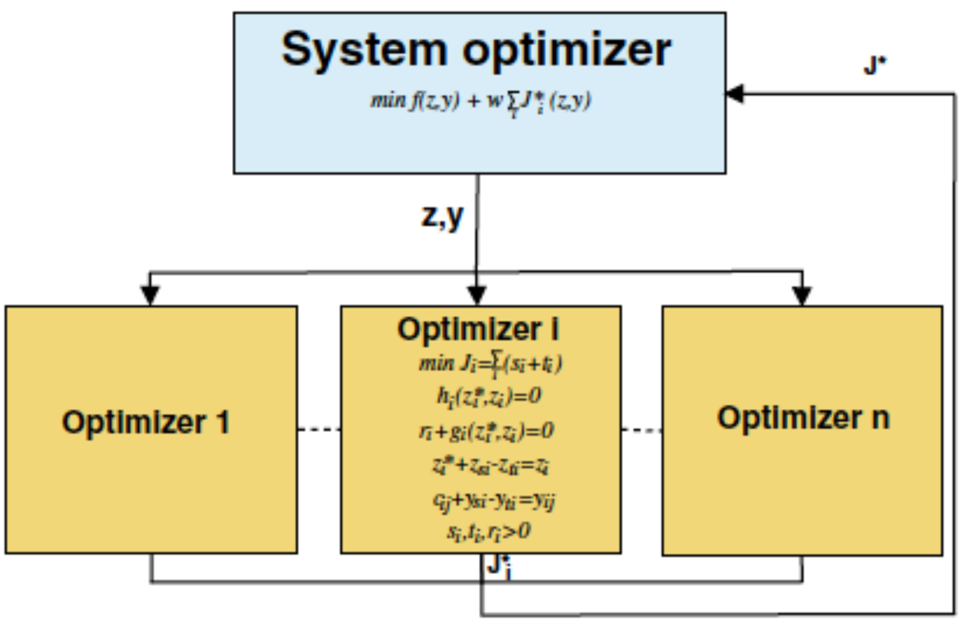

Figure 10. MCO methodology as per Balesdent et al. (2011) with modifications.

3.8 Analytical Target Cascading (ATC).

The Analytical Target Cascading methodology is in principle a method that was not directly aimed at performing MDO but to perform system targe propagation in highly hierarchical systems, with the intent to satisfy a feasible overall design in the context of these targets. Thus, its application as a design method is mostly used in the industry, where clear targets to specific processes are already known and set, and the only remaining challenge is to find the most optimal way of achieving them. In its MDO version, ATC functions transmitting “cascading” the set of specified targets from the system level to the lower levels, where they are optimized and then iterated back to the upper levels to be rebalanced. This process repeats until a total optimum is achieved.

The ATC MDO methodology could be seen as distant from the Vehicle launch design process, however its application becomes attractive when clear parameters are already set in regards of the objective function, such as clear space requirements, mass requirements, exact budget boundaries, etc.. When this is the case, ATC then becomes a suitable candidate when there is a chance to decompose the MDO problem and solve it under tight objectives. ATC has been utilized in a wide range of MDO problems already, such as design problems in the automotive industry and the building industry, however there is also a good level of usage in the Aerospace industry, particularly in aircraft design (Tosserams et al. (2010), Allison et al. (2006a), Allison et al (2006b)).

For the purpose of this study ATC is seen as suitable methodology for a further step in the design process of a space vehicle design, thus it is only explained conceptually however for references on the mathematical formulations available: Tosserams et al. (2008) provide the most used formulation.

Table 11. ATC Characteristics, Advantages and Drawbacks.

MDO method	**Comments / Short summary of Characteristics**	**Advantages**	**Drawbacks**
Analytical Target Cascading (ATC)	- Based on Hierarchical propagation of system and subsystem level targets that aim to decompose the MDO problem into multi levels.	- These MDO is designed to deal with large scale problems.	- The optimization problem is a perfect fit to optimization problems that can be partitioned into different subsystems that have clear targets to be met and thus cascade thru the levels downwards, however when targets are not clear or possible to be set accurately the system loses versatility.

	- The specified design targets are cascaded from the system level to the lower levels and are also rebalanced to higher levels after being optimized at the lower levels.	- Allows optimization into subsystems without major interference thus providing a good level of independence.	- For large scale projects that are not to be implemented again the effort on the gains do not compensate to much complexity in its formulation.

3.9 Discipline Interaction Variable Elimination (DIVE)

The Discipline Interaction Variable Elimination (DIVE) is one of the newest MDO methodologies to have come to light in the past 15 years. Its core concept is derived from BLISS-2000 Agte (2005) study in "A tool for application of bi-level integrated system synthesis to multidisciplinary design optimization problems". DIVE aims at setting up the optimization process decomposing it into multiple optimizers, solving at discipline level, all of which are then coupled by an MDA analysis. This MDA works with a quadratic form thus ensuring good coupling handling and convergence in comparison with other MDO methods, the global DV are calculated by the system level optimizer subjected to the global constraints, with the different inputs from the discipline optimizers. Then a metamodel process is run in order to ease the optimization load for the sublevel optimizers when inputting the variables for a next iteration.

DIVE mathematical formulation as per Balesdent et al. (2011) is as follows:

System Level:

$$\min \; f(z_{sh}) \quad \text{w.r.t} \quad z_{sh} \tag{48}$$

Subject to

$$g(z_{sh}) \leq 0 \tag{49}$$

$$h(z_{sh}) = 0 \tag{50}$$

$$a(z_{sh}) \leq 0$$

Subsystem level:

$$\min \; f_i(y_i, \bar{z}_i, z_{sh}) \quad \text{w.r.t} \quad \bar{z}_i \tag{51}$$

Subject to

$$g_i(y_i, z_{sh}, \bar{z}_i) \leq 0 \tag{52}$$

$$h_i(y_i, z_{sh}, \bar{z}_i) = 0 \tag{53}$$

MDA coupling variable solving:

$$\min \; \left\| c_i(y_i, z_{sh}) - y_i \right\|^2 \quad \text{w.r.t} \; y_i$$

The subsystems use meta-models to compute their local functions and the result is the vector a_i.

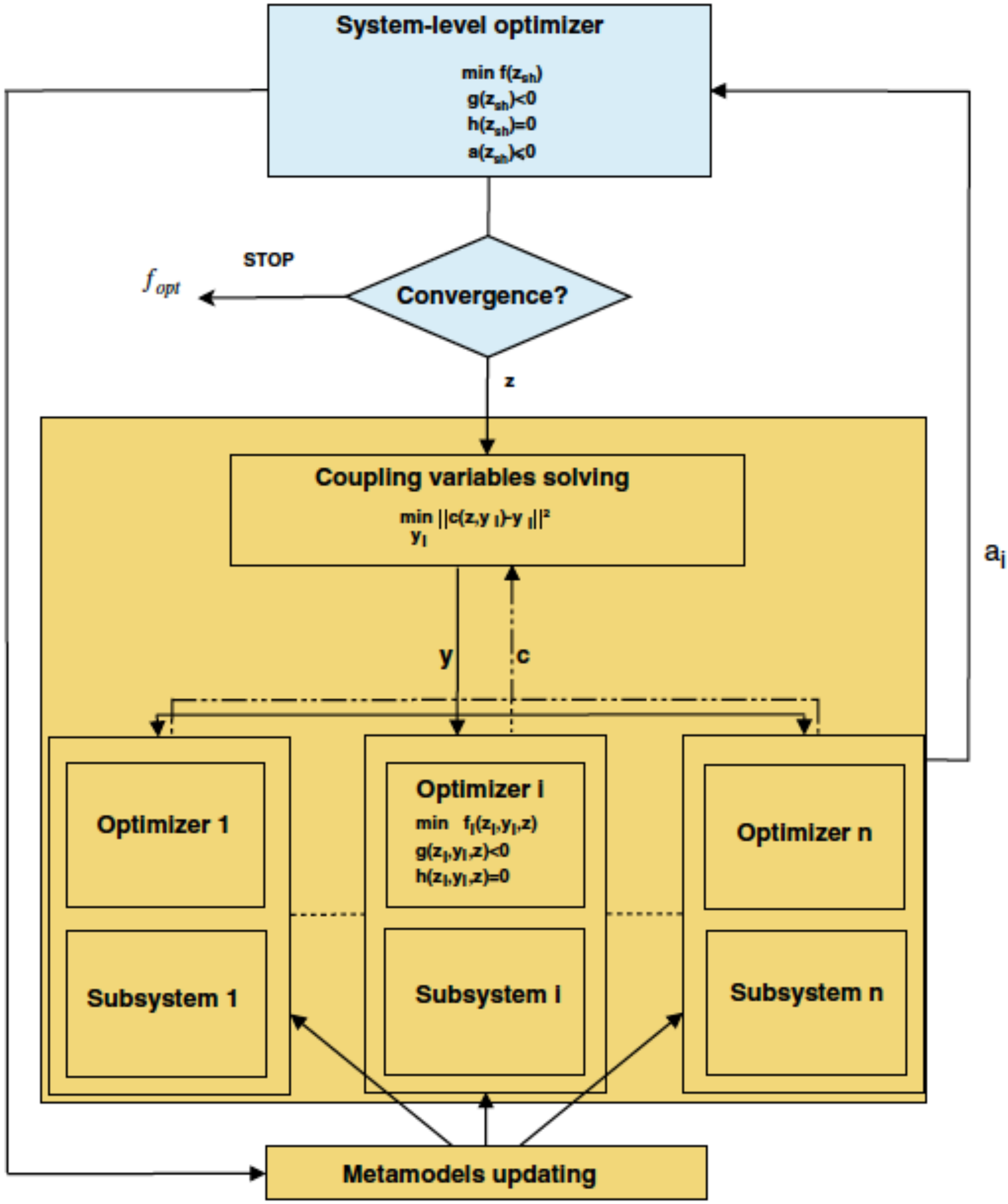

Figure 11. DIVE methodology as per Balesdent et al (2011).

Table 12. DIVE Characteristics, Advantages and Drawbacks.

MDO method	Comments / Short summary of Characteristics	Advantages	Drawbacks
Discipline Interaction Variable Elimination (DIVE)	- MDO method focuses on the use of meta models to improve the optimization problem.	- Allows for engineering team interaction in the construction of the meta models for the subsystems.	- Too much dependency on meta model creation thus allowing for inconsistencies when these are not accurate.
	- The meta models allow subsystems to set its own optimization sub functions and then evaluates the results through a global optimizer at the system level.	- Adaptive meta models can me created to improve the optimization efficiency	- Implementation of this system although has several advantages it implies great effort on design and implementation phases, that could pose high economic impact.
	- The process iterates until there is feasibility of the meta-model input and an optimal solution is found.		

CHAPTER 4: CONCURRENT ENGINEERIGN PROCESS (CE) IN THE DLR INSTITUTE OF SPACE SYSTEMS, BREMEN.

Concurrent Engineering is a methodology also known as simultaneous Engineering, whose main aim is to break the traditional way of designing complex Engineering systems by the introduction of a parallel concurrent run, in which the different stages of the design task are performed simultaneously instead of sequentially. If correctly performed the CE methodology is a powerful tool to speed up the early stages of the design process while also providing robust feasibility and selected efficiencies, such as cost reduction or specific objective enhancements. A summary of the reported benefits of the Concurrent Engineering application can be seen in figure 12.

Development time	**30 – 50% less**
Engineering changes	**60 – 95% less**
Scrap and rework	**75% reduction**
Defects	**30 – 85% fewer**
Time to market	**20 – 90% less**
Field failure rate	**60% less**
Service life	**100% increase**
Overall quality	**100 – 600% higher**
White-collar productivity	**20 – 110% higher**
Return on assets	**20 – 120% higher**

Figure 12. CE methodology gains vs traditional design method, Martelo et al. (2017).

As stated by Martelo et al. (2017), the German Aerospace Center (DLR) in Bremen, operates and performs CE in a Concurrent Engineering Facility (CEF) since 2007, and by the year 2017 had performed an approximate of 7 studies per year, to amount more than 60 studies on record. The CEF of DLR Bremen specializes in a system analysis laboratory whose main focus is early stage design of space systems.

The particular aim of this type of studies by DLR is to achieve early designs in the most efficient and consistent way possible, through the implementation of a CE approach which at the moment of writing this thesis is considered pretty much a matured process however still in continuous improvement. In specific the main focus of the CE team of DLR Bremen is satellite design, exploration missions and space transportation systems, however collaborations in other subjects such as life support systems, space based, and terrestrial infrastructures had been performed.

As clearly seen in figure 12, there is a significant improvement in the design process when applying a CE approach to the design however, this CE process still heavily relies on the knowledge and expertise of the participants of the CE team, and although in takes advantages in the current CAD and simulation tools available in a digital way, doesn’t fully profit from the computational advancements that, combined with methodologies such as MDO, can greatly boost the final design concept.

It is very important for the main purpose of this thesis to fully understand the particularities and structure of the CE process and CEF of DLR Bremen in order to mix the extensive study performed in regards of the different MDO methodologies available to be able to recommend a series of conclusions focused in the future integration of MDO into these CE process of DLR.

4.1 Concurrent Engineering Facilities (CEF).

The CEF are special facilities that are designed with the specific aim to provide the team of experts in the CE team with the infrastructure to perform each study, in case of DLR in Bremen, a relatively new facility is available which is integrated by a main design room and smaller meeting rooms. The facilities count with a separate dedicated server and arrangement of computers and interaction technologies that comply with the high standards of information security as laydown by DLR normative. A comprehensive diagram of this facility is shown in figure 13.

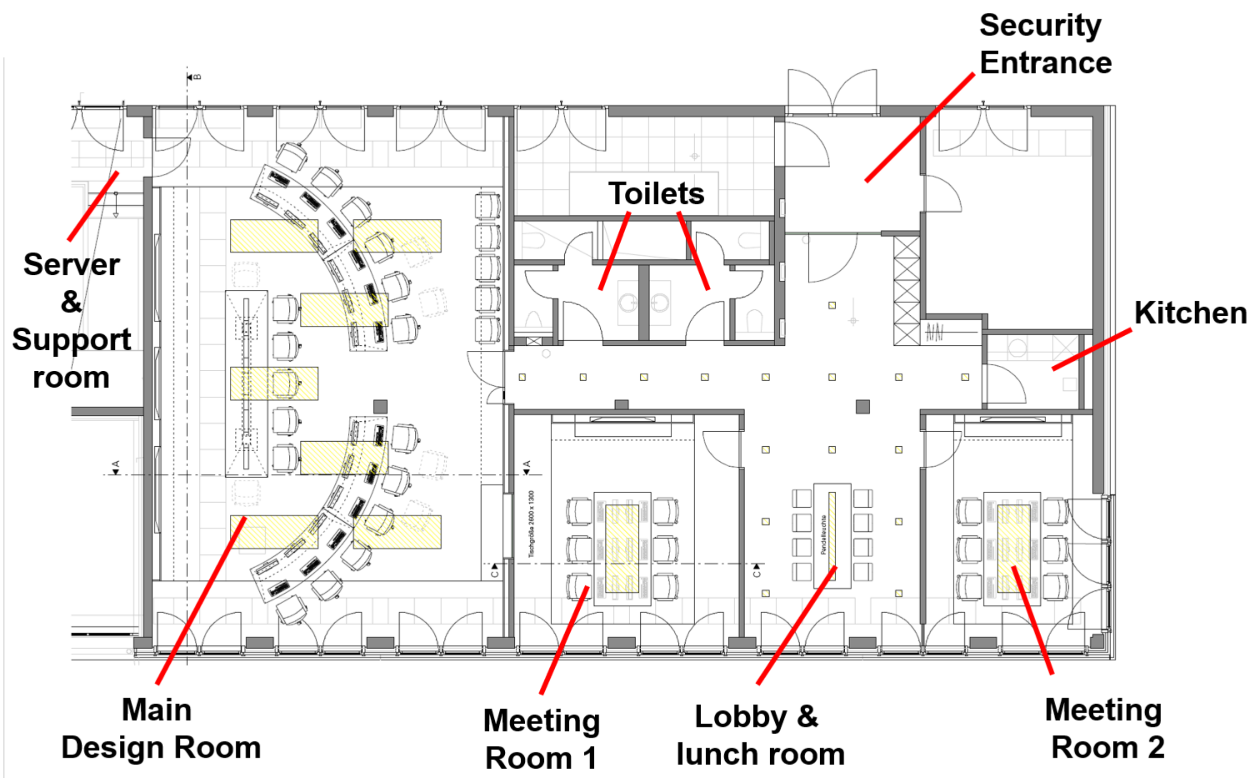

Figure 13. CEF Layout, DLR Bremen.

The main room is where the main interactions between the different team members take place, the seats are distributed between the involved disciplines and the experts conforming them. Most CE studies are presential however there is capabilities to perform them remotely if necessary.

The DLR CEF incorporates a series of software tools to aid the study participants such as CATIA, STK, etc. Among this software the main coordination and interactions are performed in a DLR own developed software called Virtual Satellite. This software aims at providing the participants with a suitable real time, shared pool of information, this is a main characteristic of a CE process and is a key factor in the way that enables all disciplines to work in parallel, while having the correct amount of communication. The core element of Virtual Satellite for CEF, is its focus on feasibility studies and its underlying data model, that represents aspects of satellite design.

4.2 Concurrent Engineering Team.

CE participants are selected depending on the particular study to be performed and it is conformed by a pool of experts within DLR and the customers. Institutions of specific research characteristics often also take part. In summary the integration of the members in the study depends highly on the type and aim of it, this is also true for the main domains or disciplines to be involved. These disciplines can of course vary from study to study but are more or less standard compared to the human participants, figure 14 shows these domains as located in the main design room.

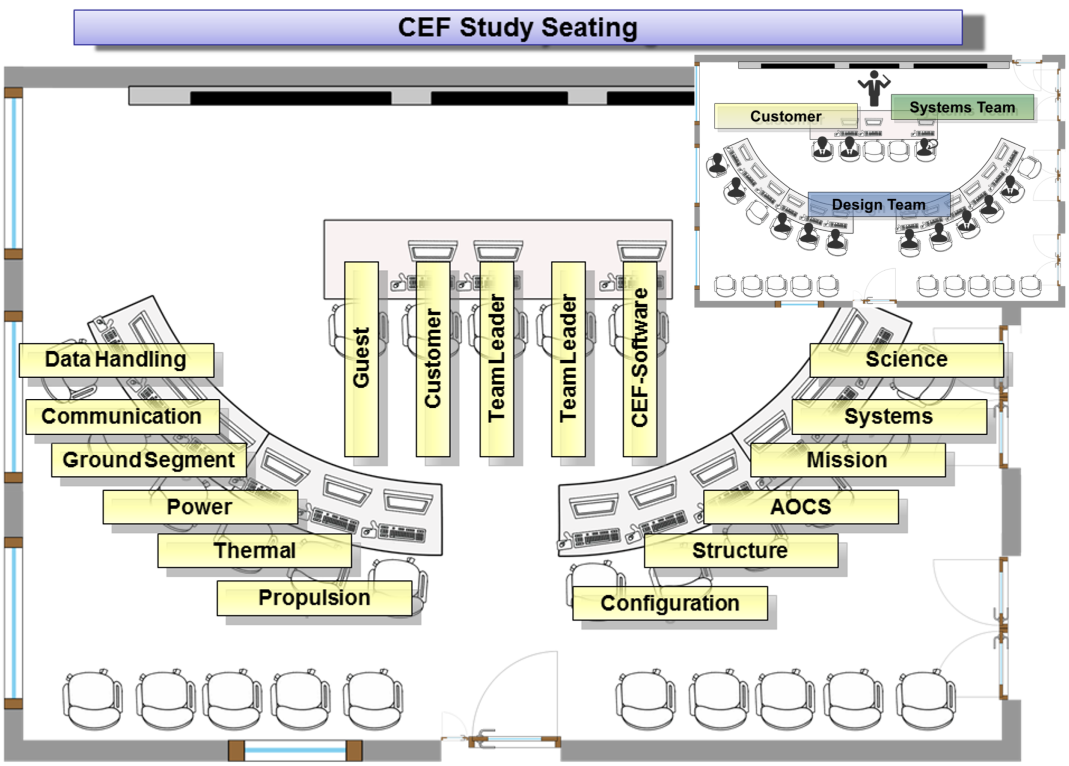

Figure 14. CEF Domains and its Layout, DLR Bremen.

All the possible disciplines can be seen listed in fig.14, this is important since it gives us not just a framework of the possible disciplines that take part in the DLR CE process but also provides insight as of the scope of possible disciplines to conform a MDO problem in a possible implementation.

The list of disciplines in fig. 14 although very illustrative is also very general, however a much more detailed input can be seen in table 12, which was provided by DLR for the purpose of this thesis.

Each CE study requires a certain set of domain experts for e.g. subsystem design, operations, risk management or cost estimation). Since the CE process is applied in a wide variety of projects, implementing a comprehensive list of all possible domains and roles is unrealistic. Nevertheless, a number of technical domains are frequent enough in the CEF to warrant a brief introduction:

Table 13. CE frequent disciplines (technical domains), from DLR.

Role	Description
Systems Engineer	Responsible for the mission and space system as a whole, tracking the overall system design, mass, power, cost, and identifying any show-stoppers. In charge of interfacing and coordinating with all domains and aspects of the design, ensuring that the requirements are satisfied and the customer goals are being met.
Payload/Science	Responsible for all the payload requirements and interface assessment and definition, as well as their refinement and optimisation. Responsible for the scientific analysis, leading to payload selection.
AOCS	Responsible for the Attitude and Orbit Control System design, mass and power budgets assessment, and its continuous refinement and optimisation throughout the study.
Power	Responsible for the power generation, distribution and storage sub-systems design, system mass and power budgets assessment, S/C power and dissipation budgets assessment, and its continuous refinement and optimisation throughout the study.
Mission Analysis	Responsible since the preliminary set-up phase of a study for mission operational orbit definition, mission orbital and navigation phases definition, trajectories and manoeuvres characterization. Throughout the study he / she is responsible for the refinement and optimisation of the mission profile and for the production and update of design data related to the navigation aspects of all the mission phases.
Transportation & Operations	Responsible for the launcher selection and define the operations scenario for the mission (commissioning, routine operations, anomalous operations, etc.).

Configuration & Structure	Responsible for the spacecraft configuration assessment and CATIA design, and its continuous refinement and optimisation throughout the study.
	Responsible for the structures design and dimensioning, and its continuous refinement and optimisation throughout the study.
Data Handling	Responsible for the on-board data handling system design, mass, power, memory and computational resources budgets assessment, and its continuous refinement and optimisation throughout the study.
Communications	Responsible for the telecommunications system design link budget and resources assessment, and its continuous refinement and optimisation throughout the study.
Cost	Responsible for the production of preliminary design industrial cost estimates and for the provision of a cost guided approach to the overall system design throughout a study.
Risk	Responsible of performing a preliminary risk assessment of the design elements defined in the study.

It is very important to note that there is no conflict between the list visible in figure 14, and the one listed in table 13, this is because some of the domains or disciplines listed formally in figure 14 are handled in practice by one or more positions listed in table 13, this of course has little to non-relevance when it comes to the actual CE process, but what it is highly important is to understand the relationship between table 13 and figure 14.

The main purpose of this chapter is to fully understand the CE process of DLR Bremen in order to select the proper formulation of a MDO methodology that could be applied to an CE design process. The selection of this MDO method might be influenced in a degree by the structure of the team and disciplines to be included in the study to be carried out, since this latter setting with a combination of other very important parameters such as the type of objective function to be optimized and the number of variables, need to be analyzed first.

4.3 DLR Concurrent Engineering process

The Concurrent Engineering Process followed in the DLR site considered in this study, follows the IPSP (Initiation, Preparation, Study and Processing) approach, which is described as follows:

Table 14. DLR CE IPSP process, from DLR.

IPSP phase		Description
1	Initiation Phase (starts months before using the CEF):	The customer and CEF personnel define study objectives (i.e. expected results), identify required disciplines (i.e. Domain Experts) and outline time planning.
2	Preparation Phase (starts weeks before using the CEF):	Preparations are both organizational (definition of team members, study schedule, agenda for first session, and funding of participants and facility), and technical (definition of initial baseline consisting of mission objectives, mission and system requirements, identification of up to three possible system concepts, and initial mission analysis), and are mostly conducted by DLR's CEF personnel, with support of the customer. Decisions are made in agreement with the customer, and the phase ends with a final definition of these two aspects, and the invitation of the Study Team components.
3	Study Phase (1-2 weeks in the facility):	At the study phase the whole team comes together in the CEF to undertake the system design. At DLR this is usually compressed into one working week with daily plenary and working sessions, but it is flexible to the customer needs and can depend on the complexities of each project. The mandatory steps of a CEF study include: • Kick-Off with presentations of the study key elements (goals, requirements). • Start with a first configuration approach and estimation of budgets (mass, power, volume, modes …) on subsystem level. • Perform iterations on subsystem and equipment level in several sessions (2 - 4 hours each),trading between several options as deemed necessary. • In between sessions, non-moderated work: subsystem design in splinter groups or individually, as appropriate. • At the end of the study, final Presentation of all disciplines / subsystems.
4	Post-processing Phase (after the study):	As the final phase of any study, the study products are compiled: • Collecting Results (each S/S provides input to book captain) • Evaluation and documentation of results • Transfer open issues to further project work • Implementation of lessons learnt into the CE-process

Overall a Concurrent Engineering Process for design is a powerful development that allows parallel collaboration between experts in real time, allowing a feasible, cost efficient design to be achieved faster.

However, it is still a very much human attached process, and the degree of success cannot be compared in terms of its optimality regarding all possible outcomes of the final design, but just in terms of the feasibility and optimality of this design compared to the traditional sequential design process. Here is where a MDO method in combination with the current characteristics of the CE process are the perfect match. This in deed is because the CE process itself is already an iterative process that aims to have the most optimal and feasible design in a short time frame, however as all human processes and endeavors it is attached to the human speed, and human failure to be able to analyze all possible design paths, MDO then is the next step, that allows to combine the human creativity and expertise with the powerful computational tools now on hand, not just as CAD side helps, or simulation aid tools but as of main design exploration tools.

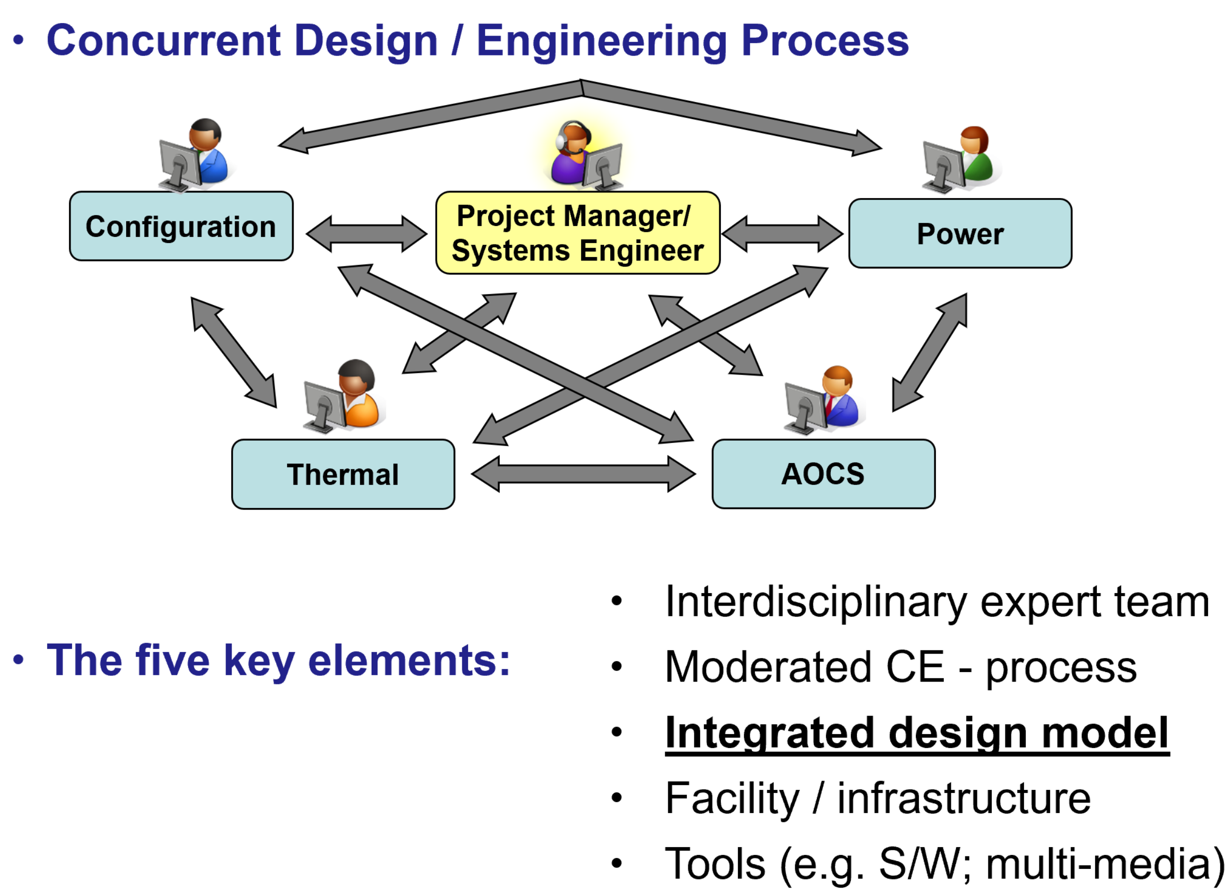

Figure 15. CEF Domains design process exchange example, DLR Bremen.

CHAPTER 5: MDO METHODOLOGIES APPLICATION RECOMMENDATIONS INTO DLR CE PROCESS.

5. MDO and the DLR CE process

After Chapter 4, where a summarized overview of the Concurrent Engineer process of DLR Bremen and CEF was reviewed and described, now it is time to combine the knowledge of the CE process with the study performed in chapter 3 about the different MDO methodologies and to select the possible methodologies that could render a successful result to the CE process of DLR.

For a practical MDO application into any design process there are two main challenges that need to be identified and dealt with:

- The selection of models and analysis methods that properly fit into the problem to be solved (correct selection of the MDO method) and,
- The selection of the mathematical solution methods to be employed to solve the optimization problem.

Prior to address the first challenge, it must be stated that no CE design process is equal in terms of its aim, objective, team members and resources available for the design (apart from the CEF), and thus there is no unique MDO selection that can be made which will render the best results for all CE studies, as these studies are non-equal one from the other an adaptation process needs to be performed in order to select the proper MDO per CE project.

Even when there is no CE project identically solved or formulated, there is a constant in terms of the composition of the teams and regarding the disciplines that conform them, this fact needs to be observed, as it is almost standard among all projects and provides the proper framework to select the MDO methodology that might be the best fit. It is also important to note that there is a number of disciplines involved in each CE study, that have very strong couplings between them. These couplings are in the form of shared variables and or inputs-outputs.

The CE process of DLR is in itself an analog to a MDO method, with the difference that it is performed by humans instead of computational algorithms, and thus subjected to its human limitations. Figure 15 shows this in a very graphical way, there is a “centralized optimization figure” in the form of the project manager in the center, coordinating and deciding (or compiling/coordinating and guiding the decisions) on the final design with inputs from each discipline expert. In this sense, each of the disciplines can be seen in MDO terms as a sub level optimizer, which deals with its own state variables and its own optimization to aim the global design. Of course there are concurrent interactions between the other disciplines due to the shared design variables and shared impacts on other designs (such as inputs or outputs) and these are coordinated via a common data base, direct communication and/or via a project manager intervention in the center, the latter being analog to the way MDO deals with couplings and constraints; there is also in the list of the five key elements as considered by DLR the use of tools and integrated design models, these could be considered analog to the different aid models that are used in some of the MDO methodologies studied in chapter 3 in order to improve the results of the optimization at the sub level stage or provide clearly defined design spaces (surrogate models, meta models, response surfaces models, etc..).

The analysis performed here is set then to which of the MDOs studied in chapter 3 can resemble this behavior and thus enhanced with its algorithm implementation the CE process. From this analysis and also due to the literature review of the performance of its method, BLISS-2000 is the obvious candidate: its analog with the actual process in which CE takes places is evident. Both have a construction that is dependent on discipline individual optimization processes, each of these processes in the form of disciplines conducts its own optimization process but includes the interactions (couplings) with the other disciplines, ultimately to be controlled by the system optimizer.

Even more relevant to a possible implementation is the advantage of the use of response surfaces or supplementary computational aid tools per discipline. This is the case in BLISS-2000 and fits well into the CE design process too without needing specific coding to automation but allowing human interaction per discipline and aiding the robustness of the overall optimization as well as its reliability.

BLISS-2000 is also a gradient based optimization method, although other mathematical formulations can be used for the local sub level optimizer per discipline, for example in the case of variables with discrete behavior (e.g. only integer values). This means that a great deal of knowledge regarding the governing equations per discipline needs to be known, in order to efficiently perform gradient based calculations such as the Hessian Matrix. This, as per the study performed on the CE process by this author, is available in most CE study cases or its formulation is fairly achievable, an example is the thesis work performed by Florian Ruhhammer (2012) under “Darstellung der Startmasse eines Satelliten-Modells einer CE-Studie als Funktion der Komponentenmassen”.

The work of Ruhhammer consisted in listing and manipulating all the related equations in a CE study of DLR and to put them in function of the mass, thus generating a general equation that was a sum of the different masses of the different components, such equation can be used for instance, as an objective function in a MDO study and all different domains can be optimized in function of the mass. Such a function has the necessary structure to efficiently perform gradient based calculations.

The example above is important because is a precedent of what needs and can be done as first steps in order to perform an MDO analysis and is key in order to guide further studies with the aim of numerically comparing the performance of different MDO methods suggested in this thesis. It is also important to note that even though BLISS-2000 remains a good starting point, for this precise example in regards of the mass a good adaptation can be made of AAO as it fits well into the level of complexity of the example hence supporting the thesis that there is no particular single method that performs best for all CE projects and even when BLISS-2000 might seem qualitatively easier to adapt to most CE studies, it could not always be the best choice, and a more precise mapping based in numerical quantitative comparison is needed in order to aid selecting the methods more accurately for future CE MDO implementations.

Nevertheless BLISS-2000 can profit from the CE structure of experts allocated in each discipline by having clear boundaries and search spaces for the different variables to be optimized which is also enhanced by the method formulation of weight coefficients.

Another important fact that makes BLISS-2000 a suitable candidate for its implementation with process such as CE is the usage of DOE (design of experiments) in parallel with the surrogate models, this allows for the reduction of uncertainties and add robustness to the optimization process in the MDO, a useful illustration of this is shown in figure 16. in this case the BLISS-2000 method is shown in the form of a XDSM (Extended Design Structure Matrix) Martins and Lambe (2013).

Overall it can be said that BLISS-2000 is an obvious candidate for a study and further analysis into detail regarding its possible adaptation as the leading MDO for the CE process of DLR, nonetheless is not the only one. From the previous analysis of the CE process as an MDO process in itself, adaptations can be performed to approach any of the multi level methods described in chapter 3, however the ultimate decision will depend on the size of the problem to be optimized, the mapping of the disciplines and its interactions, and the computational power available as well as the time for an MDO implementation. This needs to be performed in the very early stages of the CE process, as in table 14 phases 1 and 2, in order to provide a visualization path for the successful MDO selection and implementation, table 15 is formulated, which for ease of visualization maintains the core elements of table 14 but adds per IPSP phase the correspondent MDO Analysis phase to be performed.

Table 15. DLR CE IPSP process with MDO.

<table>
<tr><th colspan="2">IPSP phase</th><th>Description</th><th>MDO Analysis phase</th></tr>
<tr><td>1</td><td>Initiation Phase (starts months before using the CEF):</td><td>The customer and CEF personnel define study objectives (i.e. expected results), identify required disciplines (i.e. Domain Experts) and outline time planning.</td><td rowspan="2">Based on the outputs of phase 1 and 2 the following analysis needs to be performed:
1. Create a map of the objectives of the project with clear expectative as well as already physical constraints (resources, budget, etc.)
2.Create a map of the disciplines involved to achieve the objectives defined by phase 1, and list as accurately as possible each discipline focus and possible variables, as well as the description of the functions (linear, nonlinear, continuous, non-continuous) needed to achieve the disciplinary contributions and the shared variables between them.
3. Create a graphical representation of the CE process to be performed such as in figure 15 but allocating the elements of points 1 and 2.</td></tr>
<tr><td>2</td><td>Preparation Phase (starts weeks before using the CEF):</td><td>Preparations are both organizational (definition of team members, study schedule, agenda for first session, and funding of participants and facility), and technical (definition of initial baseline consisting of mission objectives, mission and system requirements, identification of up to three possible system concepts, and initial mission analysis), and are mostly conducted by DLR's CEF personnel, with support of the customer. Decisions are made in agreement with the customer, and the phase ends with a final definition of these two aspects, and the invitation of the Study Team components.</td></tr>
<tr><td>3</td><td>Study Phase (1-2 weeks in the facility):</td><td>At the study phase the whole team comes together in the CEF to undertake the system design. At DLR this is usually compressed into one working week with daily plenary and working sessions, but it is flexible to the customer needs and can depend on the complexities of each project.
The mandatory steps of a CEF study include:
• Kick-Off with presentations of the study key elements (goals, requirements).
• Start with a first configuration approach and estimation of budgets (mass, power, volume, modes …) on subsystem level.
• Perform iterations on subsystem and equipment level in several sessions (2 - 4 hours each),trading between several options as deemed necessary.
• In between sessions, non-moderated work: subsystem design in splinter groups or individually, as appropriate.
• At the end of the study, final Presentation of all disciplines / subsystems.</td><td>Based on the tasks performed and the available information from the previous MDO task, perform a suitable MDO selection from the list of MDOs available, analyze the potential computational resource needed when performing the final selection, and start the construction of the equations map and interactions.

If possible the construction of the algorithm is to be performed in this phase in the best case accompanied by the creation of the data model, and iterated with test runs to validate performance and convergence times.

Full run of the MDO and results analysis by the CE team needs to be performed.</td></tr>
</table>

4	Post-processing Phase (after the study):	As the final phase of any study, the study products are compiled: • Collecting Results (each S/S provides input to book captain) • Evaluation and documentation of results • Transfer open issues to further project work • Implementation of lessons learnt into the CE-process	As a final step a retrospective review of results needs to be performed, and an evaluation of the MDO method selected and the mathematical solution used performed. Results should be kept in a data base, for easy use to refine the next study MDO selection with lessons learnt or perform variations on the method or the math and analyze the results, thus creating an iterative loop for improvement.

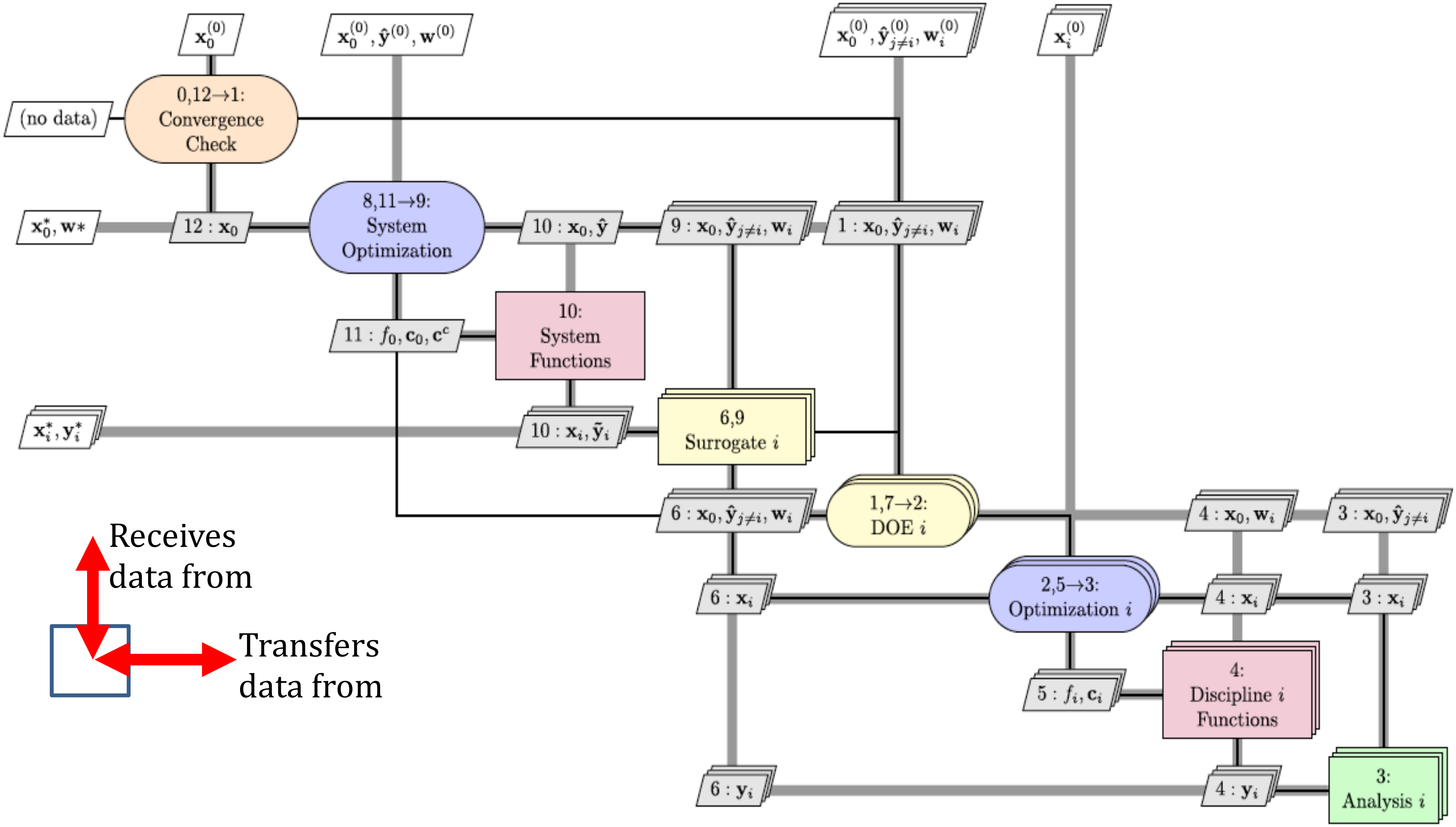

Figure 16. BLISS-2000 XDSM Martins and Lambe (2013).

Reliant on the independent analysis performed as suggested in table 15, a comprehensive selection of MDO method can be done by the CE team as of which MDO methodology fits best to the CE study to be conducted, or if any efforts really fit well at all into the main objective of the project.

Once a suitable MDO is selected the use of Martin and Lambe (2013) XDSM is most recommended and tools such as “GEMS: A Python Library for Automation of Multidisciplinary Design Optimization Process Generation” Gallard et al. (2018) can be used.

As important as the selection of the MDO method to be used, the mathematical formulation to be implemented for the actual solution problem is very important and must not be confused with the selection of the MDO method, the method depicts the structure in which the problem will be laid down to allow for the best path for optimization. The mathematical formulation hence will be in charge of executing the method selected and must be in accordance with this. In the case of BLISS-2000 for instance, since the method formulates each domain as a black box with its own optimizer and sub level surrogate models and possible DOE, the mathematical formulation for each sub level optimizer can vary from domain to domain, providing each discipline with the flexibility to adapt the mathematical algorithms to the particularities of its particular optimization function.

5.1 Important Remarks and Recommendations

The following is a set of recommendations for the selection of the MDO process and its implementation:

1. It is of the view of this author and in combination with the thesis supervisor, that whatever MDO is selected for the purpose of implementation in the CE process of DLR, extra personnel is needed (i.e. the domain “MDO Simulation” could be created and a “MDO Architect” expert summoned), particularly in the early stages depicted in table 14 as phase 1 and 2, for which the overall layout of the study needs to be planned and thus the analog with the MDO methodology created, this will enhance not just the MDO selection but the code implementation that goes with it.
2. Although not explicitly used in this thesis for explanation purposes, the approach of Martins and Lambe (2013) XDSM method to view the MDO methodology is most recommended when in implementation phase. A set of these diagrams is included in the annexes of this thesis.
3. The expertise must not be ruled out of the implementation of the MDO at least in the early implementations but needs to be put to work to define the clear search space for optima. This has to be performed both by the CE team members and also the involved clients, since a clearly defined search space will render faster results in regards of convergence times and a much more robust result regarding the final design.

4. When not explicitly needed the search for global optima is recommended to be avoided, since projects in most cases have clear budget boundaries and clear constraints. The aim of MDO at least in practical applications should be to find optima into the context of the available resources and limits. The search for global optima then needs to be left for academic purposes only or when the resources and team decision deemed so feasible. If the interest is switched from a practical to a more out-of-the-box design search, a completely different approach could be taken, such as using heuristic methods to search for global optima post processing or in additional workshops before a full CE study.
5. Enhance interaction is recommended with DLR Institute of Systems Architectures in Aeronautics, Hamburg; as quoted in the bibliography of this thesis there is solid research already performed as of the implementation of MDO methodologies but in the area of Aeronautical systems. A possible collaboration could be the invitation of support personnel in line with recommendation 1 of this list, thus including a further discipline specialist.
6. In order to correctly implement an MDO methodology an audit on the computational capabilities of the CEF is recommended. This audit much alike the energy audits already performed by the industry since several years, should be carried out by experts on the subject of computational applications and algorithm design this can be evaluated only after a sufficient number of MDO analysis, as recommended in table 14, phase 1 and 2, had been performed to already concluded CE studies. This in combination with a possible improvement of the current local servers of the CEF will prepare the facility for a correct MDO methodology implementation, without causing delays in the CE process.

Conclusions

- Even though there is a clear similarity between BLISS-2000 and the CE design process of DLR, which makes it in qualitative terms applicable for implementation into the CE design process, these cannot be assumed to be the only or the best method per se to be used, and thus a good degree of success depends on performing further studies with the purpose of quantitative benchmarking the list of MDO methodologies proposed in this Master study. In regards of its quantitative performance, for this purpose there is a large existent data base of more than 60 concluded CE projects, as stated by **Martelo et al. (2017)** thus a final decision needs to be achieved and a clear pathway for the implementation of MDO created, based on the numerical comparison and bench marking of the different MDO methodologies and not just the qualitative study performed in the course of this thesis. For this purpose and due to the large scope and amount of work required a PhD research should be the most optimal method.
- Mathematical optimization methods and MDO methods are as state above different in concept, however both are needed for a successful optimization of a design thru MDO, both need to be selected in parallel always considering the effect of the possible combination, and not its separated effect.

- The MDO methodologies research field is a broad spectrum of authors that aim at different goals. One of these goals is to achieve practical, cost efficient implementation. This line of research is as of the literature research performed in this thesis, lead by the aerospace sector, specifically in regards of aircraft design, a penetration and collaboration of this large aerospace sector needs and is most wanted with the space sector, specifically within DLR circles. (i.e. AGILE project)
- Although MDOs will enhance the performance and search of optimum designs in the DLR CE study processes, maturity is still to be achieved in that regard prior to move to a complete MDO formulation of the design problem, thus the early stages of any possible MDO implementation are to be still an aid to the current experts and not a complete hand over of the design process to the MDO computational abilities.

APPENDICES

APPENDIX A

ANNEX 1: MATHEMATICAL BACKGROUND

It is highly important for the complete understanding of this thesis to have a strong background in mathematics, a general understanding of basic concepts is necessary such that there is a good level of assimilation into the mathematical description of chapter 3, and more important, the mathematical language used in most of the analysis.

The purpose of this annex is not to provide a complete lecture into the necessary mathematics but to list them in order to provide the reader with a guideline of the concepts needed, to provide a clear classification of the main mathematical optimization methods that are used by the various MDO methods described in this thesis and to make clear the distinction between MDO method and mathematical optimization method.

It is assumed however that a basic mathematical background as of Derivates, Hessian, Matrixes, Linear Equations, Roots finding, and other basic calculation are already known by the reader. Hence, we list only some of the main concepts needed and that are beyond basic math as follows:

- Minimization of a function.
- Newton and Gauss methods.
- Lagrange multipliers.
- Pareto frontier.
- Hessian Matrix.
- Response surfaces, meta models, surrogate models, emulators.
- Penalty functions (weights).
- Slack variables theory.
- Residuals.
- Random and fixed search.
- Stochastic methods.
- Ruled based methods (heuristics).
- Gradient based methods.

For the purpose of this thesis it is pointless to explain each of the terms and concepts listed above because doing so will defer from the main aim of it, thus the purpose of this annex is not to explain this concepts but to clearly list them and guide the reader as of the reference used to clarify them. The main book that used in the literature review of this thesis as pivotal support for all mathematical concepts is Keane, A. J., & Nair, P. B. (2005). “Computational Approaches for Aerospace Design”, especially the chapter 3, which refers to “Elements of Numerical Optimization” as previously mentioned the purpose of this annex is not to re write such explanations, but to make sure the reader is aware of them, and provide a suitable guide for an external consultation.

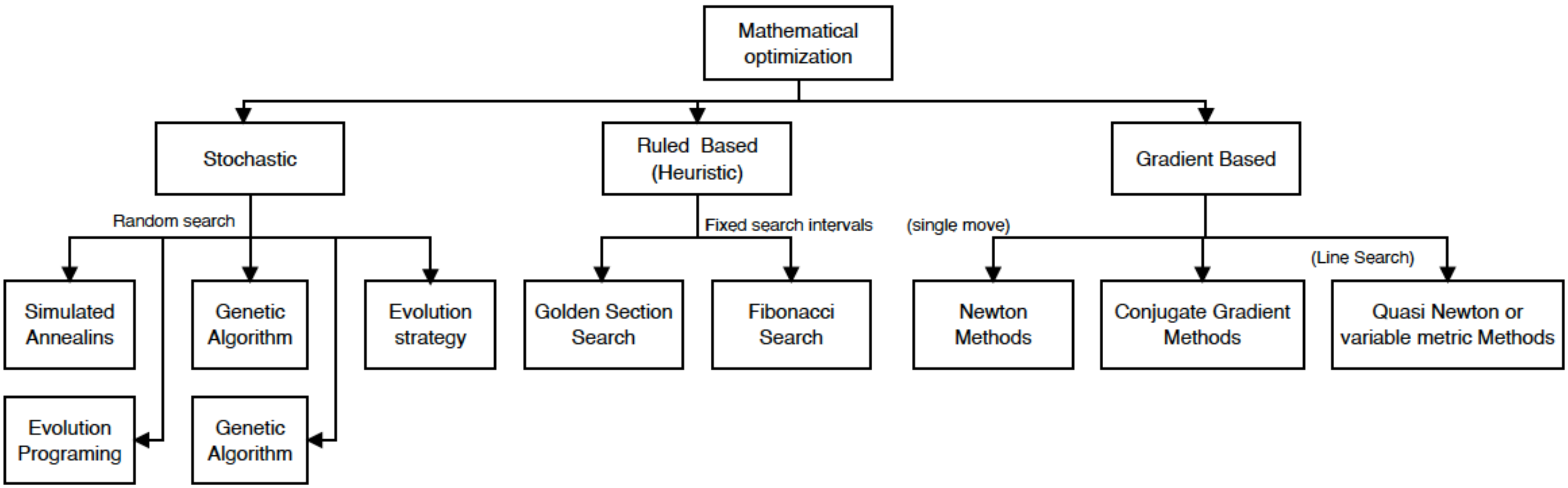

Figure 17. Mathematical optimization techniques.

Mathematical optimization methods must not be confused with the MDO, both must be selected in parallel and in accordance with the desired problem to be solve, however they are not the same, and more so the mathematical method that selected will greatly influence the cost and efficiency in which the MDO method finds the solution. For a stricter definition of each of the elements in figure 17. the book referred above is the best and first option.

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