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Identification of Damage Parameters in the commercial code LS-DYNA

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Time was invented to keep everything from happening all at once. Space is
what prevents everything from happening to me.

[John Archibald Wheeler]

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Abstract

During plastic deformation, materials can suffer damage. The rate at which this damage progresses varies significantly from one material to another. In order to improve the ability of finite element analysis for failure prediction, continuum damage models are being integrated in codes, in order to contribute for enhancing the optimization of sheet metal forming processes. An example is the integration of the enhanced Lemaitre's damage model in the LS-DYNA. However, to explore the potentialities of this model, it is important to improve the knowledge concerning the identification of its parameters. The present work focus on the development of a strategy to perform the identification of these model parameters. In this context, sensitivity analysis and optimization tools available on LS-OPT were explored.

The inverse damage parameters identification strategy is developed considering the availability of force-displacement experimental results from: uniaxial tensile and Nakajima tests. The material orthotropic behaviour and the isotropic hardening parameters are identified using the results from uniaxial tensile tests. Based on the sensitivity analysis performed to the damage parameters, the identification procedure proposed includes five damage parameters. The procedure is based on the application of the Adaptive Simulated Annealing algorithm to metamodels, built considering a Sequential Response Surface Methodology, in order to minimize the computational time. The results show that the procedure is sensitive to the user-defined starting point. In this context, it is not possible to state which of the solutions obtained corresponds to the best description of the material mechanical behaviour. A strategy to reduce the number of parameters is also proposed, based on the analytical calculation of the initial damage energy release rate. This enables the identification of the damage parameters with a similar accuracy in a lower number of iterations.

Keywords Damage, Parameter identification, Optimization, Sensitivity analysis, Tensile test, Nakajima tests.

Resumo

Durante os processos de deformação plástica, os materiais podem sofrer dano. A velocidade a que o dano se desenvolve varia de material para material. De modo a aumentar a capacidade da análise com o método dos elementos finitos na previsão de dano, têm sido integrados nos programas de simulação modelos contínuos de dano, de modo a contribuir para melhorar a optimização de processos de deformação de chapas metálicas. Um exemplo é a integração do modelo melhorado de dano de Lemaitre no programa LS-DYNA. De qualquer modo, para explorar as potencialidades deste modelo, é importante melhorar os conhecimentos relativos à identificação dos seus parâmetros. O presente estudo foca-se no desenvolvimento de uma estratégia para realizar a identificação dos parâmetros deste modelo. Neste contexto, explora as ferramentas de análise de sensibilidade e optimização disponíveis no programa LS-OPT.

A estratégia de identificação inversa dos parâmetros de dano é desenvolvida considerando a disponibilidade de curvas força-deslocamento experimentais de ensaios de tracção uniaxial e ensaios de Nakajima. O comportamento ortotrópico do material e os parâmetros isotrópicos de encruamento são identificados utilizando os resultados do ensaio de tracção uniaxial. Baseado na análise de sensibilidade, aplicada aos parâmetros de dano, o processo de identificação proposto inclui cinco variáveis de dano. O procedimento é baseado na aplicação do algoritmo “Adaptative Simulated Annealing” a metamodelos, considerando a estratégia de redução de domínio “Sequential Response Surface Methodology”, de modo a minimizar o tempo computacional. Os resultados mostram que o procedimento é sensível ao conjunto de parâmetros iniciais definidos pelo utilizador. Neste contexto, não é possível definir qual das soluções obtidas descreve melhor o comportamento mecânico do material. É também proposta uma estratégia para reduzir o número de parâmetros, baseada no cálculo analítico da velocidade inicial de libertação de energia de dano. Isto permite a identificação dos parâmetros de dano com uma precisão similar e um menor número de iterações.

Palavras-chave: Dano, identificação de parâmetros, optimização, análise de sensibilidade, ensaio uniaxial de tracção, ensaios de Nakajima.

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SIMBOLOGY AND ACRONYMS

Simbology

\tilde{A} – Effective area

A – Area where the load is applied in the physical space

A_0 – Initial area of the specimen

A^D – Damaged area

\mathbf{C} – Fourth-order tensor of elastic constants

C, n, ε_0 – Hardening parameter

C_{r_k}, Q_{r_k} – Hardening parameters

\dot{D} – Damage evolution rate

D – Damage internal variable

D_c – Critical damage

E, T, k_B – Boltzmann distribution parameters: Probability distribution energy, Temperature, Boltzmann's constant

E – Young's modulus

F – Tensile load

F, G, H, L, M, N – Hill's parameters

$f(\mathbf{A})$ – Objective function

$f(\sigma_{ij})$ – Yield function

h – Microdefects closure parameter

\mathbf{H} – “Hat” matrix

h_{ii} – Diagonal terms of the “hat” matrix

\mathbf{I} – Identity tensor

l – Final gauge length

l_0 – Initial gauge length

n – Number of variables under analysis

n_t – Number of terms

$Oxyz$ – Principal anisotropy axes

p – Total number of measurement points

r_n – Coefficient of normal anisotropy

R_v – Triaxiality function

r, r_α – Lankford coefficient, measured with the specimen oriented α degrees to

RD

R^2 – Coefficient of determination

S, s, β, η – Damage parameters

S_i – Sobol's indice

S_{yy} – Variability in observations

\mathbf{X} – Matrix of design variables

$\mathbf{x}', \mathbf{v}, \mathbf{T}, \mathbf{c}, \mathbf{m}, \mathbf{n}$ – Parameters of ASA algorithm: candidate point, function for selection, temperature parameter, cooling schedule control parameters

$\hat{\mathbf{y}}$ – Vector of fitted values

\bar{y}_i – Mean of the responses

\hat{y}_i – Predicted response

Y – Damage energy density release rate

Y – Flow stress

\mathbf{y} – Vector of observations

Y_0 – Initial damage energy release rate

y_i – Actual response

α, C, D – Parameters for the hardening Voce law type

δ_{ij} – Kronecker symbol

Δl – Displacement

Δr – Planar anisotropy

$\bar{\varepsilon}_{eff}^p$ – Equivalent plastic strain in the effective space

$\bar{\varepsilon}^p$ – Equivalent plastic strain

$\boldsymbol{\varepsilon}$ – Strain tensor

$\boldsymbol{\varepsilon}^{el}$ – Elastic strain

$\varepsilon_{eff,d}^p$ – Threshold value for the equivalent plastic strain in the effective space

$\varepsilon_1, \varepsilon_2, \varepsilon_3$ – Principal plastic strains

ε_{RMS} – Root mean square error
 $\varepsilon_x, \varepsilon_f$ – Parameters to control the objective function termination criteria
 η_{triax} – Stress triaxiality
 λ – Lamé parameter
 μ – Lamé parameter
 $\tilde{\sigma}$ – Effective stress
 $\bar{\sigma}$ – Equivalent stress
 $\tilde{\sigma}_H$ – Hydrostatic Cauchy's stress tensor component
 $\boldsymbol{\sigma}$ – Stress tensor
 $\sigma_{failure}^{eng}$ – Engineering failure stress
 σ_H – Hydrostatic Cauchy's stress tensor component
 σ_{max}^{eng} – Engineering maximum stress
 σ_{vm} – Equivalent von Mises stress
 σ_y – Yield stress
 $\boldsymbol{\sigma}'$ – Deviatoric Cauchy's stress tensor component
 σ^{Exp} – Stress obtained experimentally
 σ^{Num} – Stress obtained numerically
 τ_{max} – Maximum shear stress
 ν – Poisson's coefficient

Acronyms

AHSS – Advanced High Strength Steels
ANOVA – ANalysis Of VAriance
ASA – Adaptive Simulated Annealing
CDM – Continuum Damage Mechanics
CPU – Central Processing Unit
DEM – Departamento de Engenharia Mecânica
DOE – Design Of Experiments
FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra
FEA – Finite Element Analysis
FFNN – FeedForward Neural Network

FLC – Forming Limit Curve
FLD – Forming Limid Diagram
GRG – Generalized Reduced Gradient
GSA/SOBOL – Global Sensitivity Analysis
IMA – Inpro Materialableich
INPRO – Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der
Fahrzeugindustrie mbH
LFOP – Leap-frog Optimizer
MDM – Micromechanical Damage Mechanics
MSE – Mean Square Error
NB – Nakajima Biaxial strain path
ND – Normal Direction
NPS – Nakajima Plane Strain strain path
NU – Nakajima Uniaxial strain path
PRESS – Prediction Sum of Squares Residual
RBFN – Radial Basis Function Network
RD – Rolling Direction
RSM – Response Surface Methodology
SA – Simulated Annealing
SRSM – Sequential Response Surface Methodology
SSE – Sum of the Squared Errors
TD – Transverse Direction
UT – Uniaxial Tensile Test

1. INTRODUCTION

The development of technology over the past years led to the growth of sheet metal formed products that can be found in almost all consumer products. From an economical point of view, the design and manufacturing technologies are more important to guarantee the competitiveness of each manufacturing company. In the last years, numerical tools based in the Finite Element Analysis (FEA) gained an important role, since they allow companies to save money and time. The advantage of such tools are well known and their development is continuous and indispensable towards the advance of science and technology. The implementation of new time integration techniques connected with new constitutive models has contributed for improvements in the accuracy/precision of the results. Also, code parallelization and algorithmic optimization allowed an increase of the computational performance. In parallel, the continuous development of materials, normally more resistant but also less ductile, induces new engineering challenges.

The growth in the use in industry of new materials, especially Advanced High Strength Steels (AHSS) (e.g. dual phase, TRIP), is due to their enormous advantages since they present:

- Low weight;
- High strength;
- Good crash performance.

Therefore, AHSS are nowadays widely applied in the design of automotive components, in order to reduce the weight and to increase the resistance, consequently reducing the fuel consumption in passenger cars and the carbon dioxide (CO₂) emissions rates, fulfilling the new environmental demands and safety requirements. However, they present lower ductility and higher work hardening rate when compared to conventional steels. Thus, failure usually occurs earlier and sometimes without strain localization (necking), making it harder to predict fracture occurrence. Also, it is hard to predict the mechanical behaviour of metallic sheets under complex strain paths. In fact, the use of the conventional forming limit curve (FLC) presents some limitations in the prediction of metallic sheets formability limits, particularly for AHSS, as it is known that it is not possible to predict shear cracks occurrence

(Banabic 2010). Therefore, damage models are being developed and used to try to improve the description of the mechanical behaviour of these steels, particularly the formability analysis.

1.1. Objectives

The main objective of this work is to improve knowledge concerning the damage parameters identification procedure, particularly the ones of the enhanced isotropic Lemaitre's model, implemented in LS-DYNA. The starting point was to consider the availability of force-displacement experimental results from: uniaxial tensile tests and biaxial, plane strain and uniaxial Nakajima tests. The first objective was to perform sensitivity analysis of the damage parameters in each test, in order to define different possibilities for the inverse analysis identification procedure. This could include the use of specific tests for each parameter or even the exclusion of some, less sensitive, parameter(s) from the procedure. The subsequent goal was to develop an inverse analysis procedure, enabling the fast and accurate identification of the damage parameters. The tools used in the work should be the ones available in LS-OPT.

1.2. Reading Guide

The manuscript is organized in six different chapters. After this first introductory chapter, in Chapter 2 the basic concepts of damage prediction, continuum damage mechanics and parameter identification are shortly presented.

Chapter 3 introduces the material constitutive modelling, including the isotropic elastic behaviour and the orthotropic plastic one. In this context, a brief review of the Hill'48 yield criterion is provided. Some commonly used isotropic hardening laws are also presented. Also, the principles of the continuum damage mechanics model are presented, specifically the enhanced Lemaitre's isotropic damage model, and the variables that describe the internal damage state of the material.

Chapter 4 introduces the parameter identification procedure, resuming the characteristics of the experimental tests considered and the numerical models adopted. The procedure for the identification of the isotropic hardening parameters is discussed, based on the uniaxial tensile test results. The sensitivity analysis results are presented highlighting the

effect of each damage parameter, in each test. Finally, the inverse strategy for performing the damage parameters identification is presented.

Chapter 5 is devoted to the optimization results presentation and discussion, including the analysis of the evolution of the equivalent plastic strain, damage and triaxiality, during each test.

Finally, Chapter 6 presents a summary of the main conclusions along with suggestions for future works.

2. STATE OF THE ART

Sheet metal forming is the process of transforming metal sheets into thin, non-flat pieces. The main characteristic of the components produced is the high surface area to thickness ratio. It is used in almost every sector of industrial production (ex: automotive, aircraft or food industry). In this process, several methods can be used to obtain the desired shape, being the final shape always achieved through plastic deformation. It can be classified in accordance with DIN 8582 (Normung n.d.) into five processes, depending on what type of stresses is the sheet subjected to (main direction of the applied stress):

- Forming under compression;
- Forming under tensile conditions;
- Forming under both compressive and tensile conditions;
- Forming under bending;
- Forming under shearing.

The deformation analysis in sheet metal forming is commonly based on the evaluation of the two principal strains, ϵ_1 and ϵ_2 , that occur in the sheet plane. The FEA of the forming limit is performed comparing the estimated values for these strains with the experimentally evaluated FLC, either considering necking or fracture occurrence. However, the experimental evaluation of the FLC is expensive and most of all is strain path dependent. Therefore, different approaches have been explored trying to overcome the disadvantages of the strain based FLC and avoid the laborious experimental tests involved in its evaluation.

Necking and fracture occurs consequence of the material damage. Damage is the physical process of deterioration that can lead to macroscopic collapse. It “is the creation and growth of microvoids and microcracks which are discontinuities in a medium considered as continuous at a larger scale” (Lemaitre & Desmorat 2005). In a more pragmatic point of view, it is the physical process that will lead to the material failure. Its direct measurement as, for example, the measurement of the surface’s (and interior) density of microdefects, is difficult to perform and requires well-equipped laboratories. Depending on the nature of the material, loading conditions and temperature, damage can express itself in several ways:

- Brittle damage, when a crack is initiated at the mesoscale without a large amount of plastic strain;
- Ductile damage, when it occurs simultaneously with plastic deformations larger than a certain threshold (Lemaitre & Desmorat 2005), resulting from the nucleation of cavities due to decohesions between inclusions and the matrix, followed by their growth and their coalescence through the phenomena of plastic instability;
- Creep damage, which are intergranular decohesions which produce damage and an increase of the strain rate (happens at high temperatures, involving viscosity in the plastic strain, allowing the material to be deformed at constant stress);
- Low cycle fatigue damage, when the material is subjected to a cyclic loading at high values for stress and strain, allowing damage to develop together with cyclic plastic strain (low number of cycles until rupture);
- High cycle fatigue damage, when the material is subjected to a cyclic loading at low values of stress.

For most metallic materials, damage is usually a combination of brittle and ductile response (Lemaitre & Desmorat 2005). In order to predict more accurately the behaviour of the material, some damage models have been developed in the last years, whose criteria are based either on damage accumulation or on localization. Localization damage is normally applied to materials that present softening behaviour, requiring a precise implementation and having strong finite element mesh size dependence. Damage accumulation methods keep track of the critical damage needed for fracture to occur and can be based on uncoupled fracture criteria (macroscopic approach) or coupled damage models, which can be either based on Micromechanical or Continuum Damage Mechanics (MDM or CDM).

This present work focuses on CDM models and their application on formability prediction for sheet metal forming processes. Therefore, in the following section some details concerning this type of models are given. Also, due to the importance of the FLC (in the strain space) in FEA, some details about the advantages and disadvantages of using this approach are given.

2.1. Damage prediction

A material is free of any damage if it is devoid of cracks and cavities at the microscopic scale, i.e. if its deformation behaviour is that of the material formed under the best conditions. The theory of damage describes the evolution of the damage phenomenon evolution between the virgin state and the macroscopic crack initiation. This phenomenon is not easily distinguishable from deformation, which usually accompanies it (Lemaitre & Chaboche 1985). Therefore, in sheet metal forming process the formability analysis is typically performed based on the strain state in the sheet plane, using the FLC.

2.1.1. Forming Limit Curve

In sheet metal forming process design, the forming limits are typically evaluated using the FLC, which allows estimating the split between the safe and fail regions, being possible to reduce necking, wrinkling and large deformation occurrence, by keeping the strain state in the safe area (Oliveira et al. 2011). These curves (FLC) represent the maximum sustainable formability of the component as a combination of the first and second principal strains, and can be determined either experimentally or analytically, being a good and user-friendly damage prediction method for linear strain paths. A schematic representation of the FLC is given in Figure 2.1, highlighting the safe and fail zones.

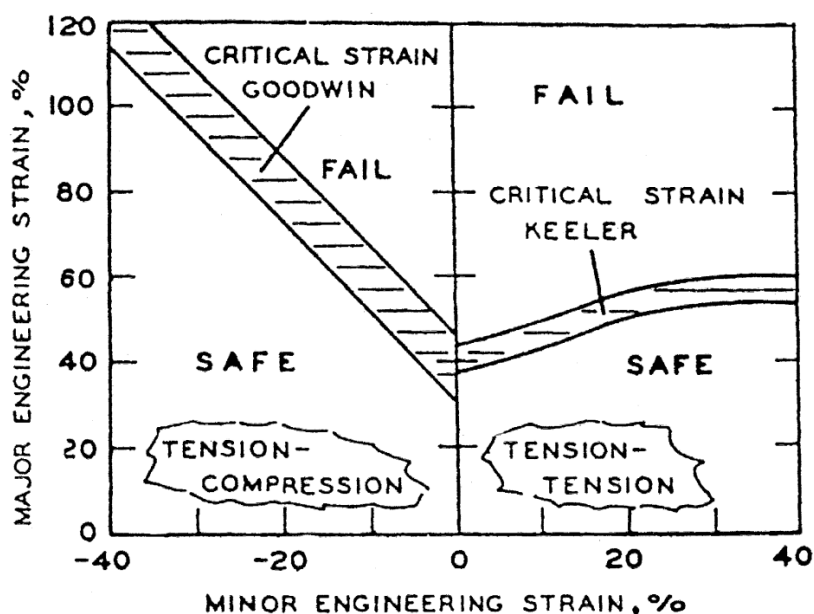


Figure 2.1 - Forming limit diagrams defined by Keeler and Goodwin (extracted from (Banabic 2010))

The experimental evaluation of this diagrams requires the measurement of the principal strains, ϵ_1 and ϵ_2 , for each strain path, up to necking or failure. The conventional procedure consisted on selecting an appropriate geometry of the test specimen, for each strain path, and cover the surface with a grid of circles, used to measure the strains at failure (fracture, necking, wrinkling). Nowadays digital image correlation techniques can be used to improve the results acquisition and minimize the impact of the analyst experience in the results. Since it is not possible to perform the test for all strain paths, the connection of all evaluated points, corresponding to limit strains according to different strain paths, leads to a FLC, which corresponds to the FLD (forming limit diagram). The knowledge of this curve enables the direct comparison of the numerically predicted in-plane principal strain with the ones determined as critical. This enables the design of processes that avoid failure occurrence. The FLC became popular because the results obtained for conventional steels and aluminium alloys pointed out that the forming limits can be quite well estimated and because it is easy to use in FEA. Nevertheless, even for these materials it is also known that the use of the FLC disables the exploitation of the material formability, since it typically leads to conservative designs. In fact, despite the extensive use of the FLC, they have several disadvantages for evaluating the sheet metal formability:

- Provide information only for the region between uniaxial tension and equibiaxial stretch under plane stress;
- They are typically evaluated for linear (monotonous) strain paths but are known to present strain path dependency, as shown in Figure 2.2. Moreover, during deep drawing each material point is typically subjected to a particular non-linear strain path, which limit cannot be predicted by the FLC, because integrated damage accumulation is not taken into account;
- Information about fracture mode and direction is not provided;
- They are not applicable if the hardening behaviour is influenced by thermal effects;
- They depend on the sample's thickness and on the material mechanical properties, which are known to present some variability even for the same supplier.

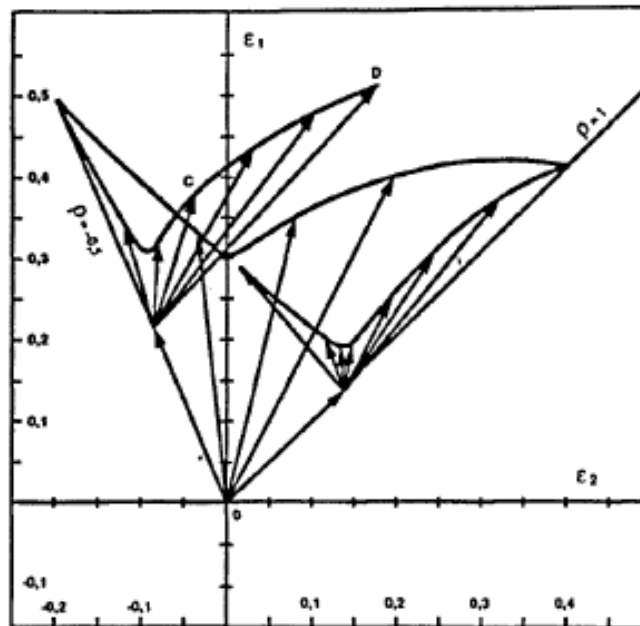


Figure 2.2-Influence of strain path on the forming limits for a steel for uniaxial tension and equi-biaxial expansion followed by several strain paths (extracted from (Butuc 2004))

Therefore, due to the enormous restrictions related with the FLC in the strain space, different approaches are being investigated. The use of physically based damage models is one of these approaches, since they are already used in crash simulations and bulk forming (Doig et al. 2014). The great progress made throughout the years in simulation codes is somewhat conducting to the point where, somewhere in the future, FLC will only be used to validate new stamped components.

2.1.2. Continuum Damage Mechanics Models

The theory of damage concerns any kind of load as well as low and/or high temperatures. The stress and strain history, for a given elementary volume element of a structure, allow the damage laws to provide, through its integration with respect to time, the damage evolution in the element, up to the point of macroscopic crack initiation. Therefore, it is expected that its use will contribute towards better optimization of metal forming processes by plastic deformation, allowing to reduce manufacturing defects.

The CDM theory is based on the introduction of a damage internal variable, D , which is related to the density of internal defects, describing the extent of micro-voids and micro-cracks in the material, before the initiation of macro-cracks. The material in the

physical space presents micro-voids and micro-cracks, while in the effective space it is idealized as a continuum. Therefore the area where the load is applied in the physical space, represented by A , corresponds to an effective area, represented by \tilde{A} . This means that the damaged area could be calculated by $A^D = A - \tilde{A}$. Consequently, the scalar damage variable, D , can be represented by (Lemaitre 1992):

$$D = \frac{A^D}{A} = 1 - \frac{\tilde{A}}{A}. \quad (2.1)$$

The model describes the initiation and evolution of the internal damage in the material by defining an evolution law for D . This way, at each instant, it is possible to evaluate the damaged area, i.e. the growth of cracks and cavities (surface density of discontinuities).

CMD models on the evolution law adopted for the scalar damage variable, D . Typically, this is a phenomenological law that tries to describe the mechanical behavior observed for the material. Thus, there is always some set of material parameters that enables the best fit between the numerical and the experimental results. For further details it is recommended to read the works (Soyarslan & Tekkaya 2010a) and (Soyarslan & Tekkaya 2010b), which were used as reference for this section.

2.2. Parameter identification

As previously mentioned, damage is not easily distinguishable from plastic deformation. Therefore, there is also a strong correlation between the constitutive model selected to describe the material plastic behaviour and the damage model. Moreover, damage can occur due to localization under non-homogeneous stress-strain state. In order to identify damage parameters it is not possible to assume homogeneous conditions for the strain path, as commonly adopted for the identification of the hardening and anisotropic parameters. Therefore, an inverse optimization method is needed for damage parameters identification. The inverse optimization method commonly adopted relies on the correlation between finite element method (FEM) results and the experimentally evaluated results, typically force displacement curves.

For the parameter identification, several methods are now available to perform both sensitivity and optimization analysis. LS-OPT includes several metamodel building methods:

- Polynomial;

- Sensitivity;
- Feedforward Neural Network;
- Radial Basis Function Network;
- Kriging;
- Support Vector Regression.

There are also several point selection methods available. They are:

- Full factorial;
- Linear Koshal;
- Quadratic Koshal;
- Composite;
- D-Optimal;
- Monte Carlo;
- Latin Hypercube;
- Space Filling.

(Stander et al. 2010)

It is important to state that a metamodel can obtain better or worse results depending on the point selection method selected. Also, some metamodels are more suitable to perform sensitivity analysis whilst others are more suitable to perform optimization of parameters itself. With practice and/or experience, one is able to decide faster and more accurately on which metamodel to use, depending on the problem. Information regarding these metamodels and the point selection methods can be found in the LS-OPT manual (Stander et al. 2010) and in many other books (Bonte 2007) (Myers et al. 2009a). To conclude the topic, the choice of the metamodel to use and the point selection method always depends on the problem in study.

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just indicates convergence, not quality of the results. Thus, it is not possible to conclude it

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