Low-Fidelity Parametric Modelling Approach for Early Design Phase

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Introduction

Satisfying all the customer requirements is not always possible. Therefore, design process needs to be agile and iterative. Design and its requirements needs to be effectively iterated.

Model-based product design using computer simulation and functional prototypes has become a standard design practice in most companies in mechanical engineering.

However, it is a general observation in several engineering design projects that simulation-driven approach takes a lot of time and that design-supporting information is not easy to achieve, especially in an early design phase when the most important decisions are made

Issues with simulation-driven approach

Issues in simulation-driven approach as being due to two main reasons:

- Firstly, simulation software is not targeted to general problem solving. Instead, it is targeted to efficient construction of simulation models.
- Secondly, those simulations usually generate only responses between input and output. This information is usually not sufficiently rich for efficient decision making at early stages.

Low-fidelity modelling

Low-fidelity models can be part of a solution for time constraint in the early design phase.

Low-fidelity prototypes are raw representations of our ideas and concepts. They help us to learn and validate those concepts in early-phase design processes.

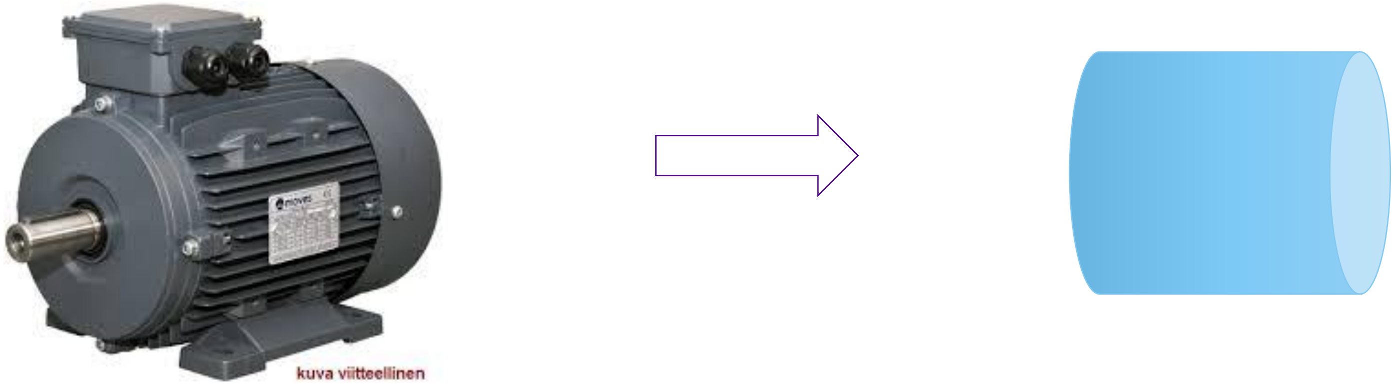
Model fidelity refers to the degree to which a model or simulation reproduces the state and behavior of a real world object, feature or condition. Fidelity is therefore a measure of the realism of a model or simulation.

Simulation fidelity has also been described in the past as "degree of similarity".

Low-fidelity modelling

In Low-fidelity approach the exact models derived from physics or geometry are simplified to their key features.

Their drawback is typically a low modelling accuracy but the key benefit is the fast capability to provide design information



Axiomatic design

Axiomatic design proposes a mapping between design parameters **DP** and system characteristics **CH**. This can be summarized in a matrix representation:

$$[CH] = [A][DP]$$

where **A** is a design matrix, **CH** is an array of system characteristics and **DP** is an array of design parameters. Matrix **A** is creating a mapping between design parameters and system characteristics.

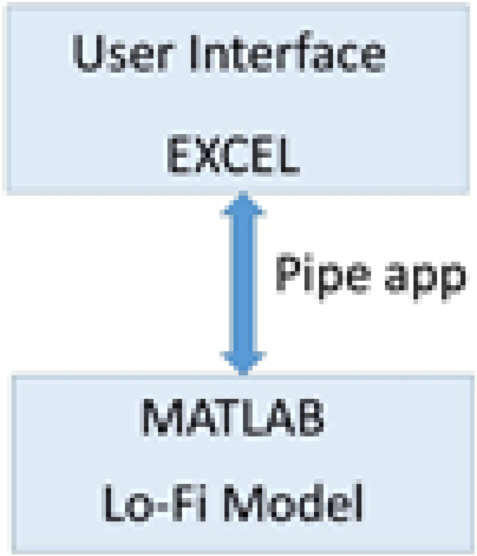
Axiomatic design

A serious limitation is linearity of the matrix equation because most of the system model equations in mechanical engineering are nonlinear. This drawback is resolved by using non-linear model equations to be linearized at an operation point. Therefore, matrix **A** is defined at this point.

Another issue with this approach is that it is not always possible to define an explicit function between a system characteristic and a design parameter. In such cases, a heuristic modelling approach needs to be used.

EAD-tool

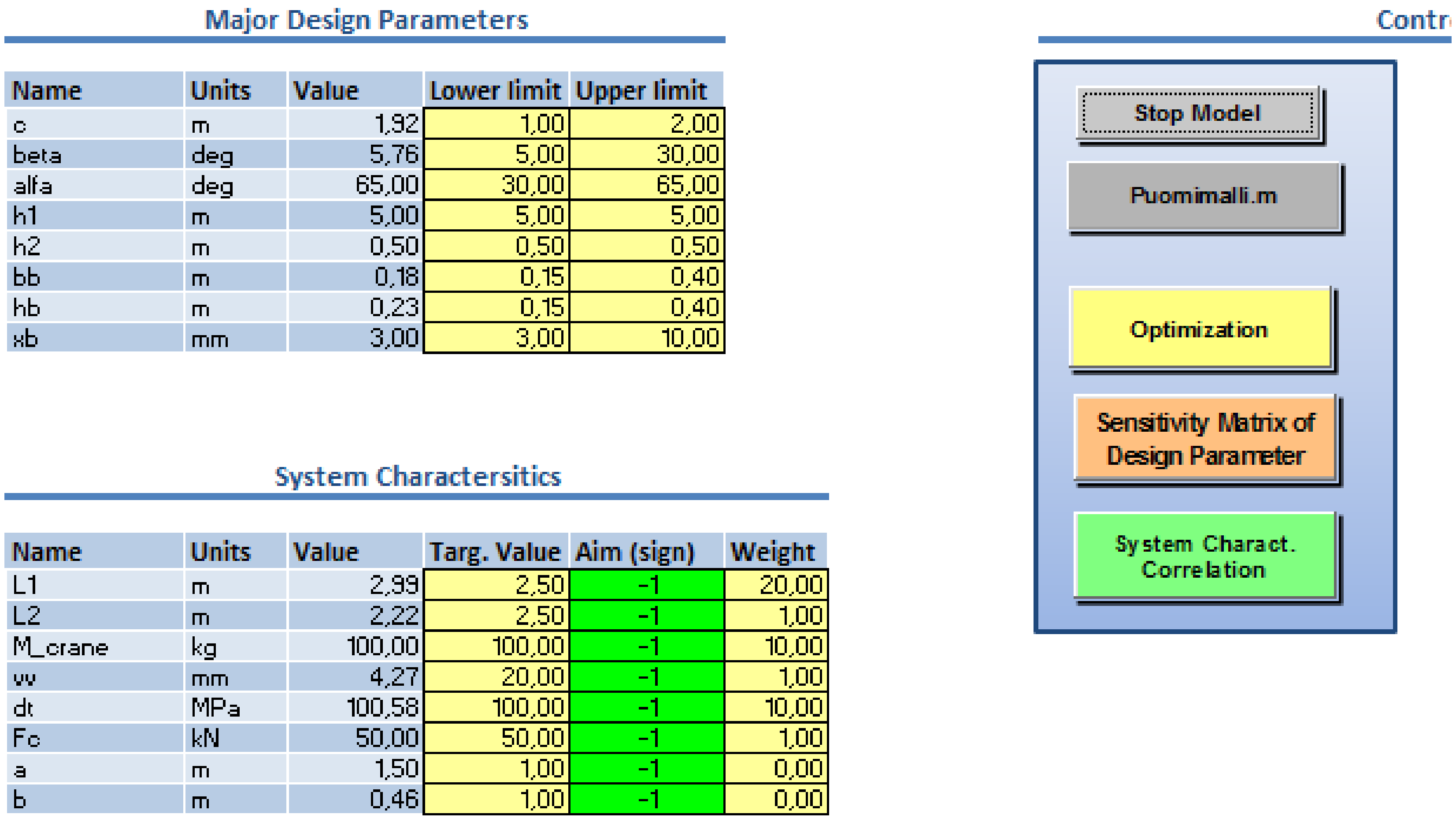
Engineering Design Analysis Tool



Fuctionalities:
- Direct analysis
- Multi-target optimization
- Sensitivity analysis of design parameters
- Correlation of system chracteristics

Low-fidelity model that connects system characteristics to design parameters

User Interface of EDA-tool



Major Design Parameters

Name	Units	Value	Lower limit	Upper limit
c	m	1,92	1,00	2,00
beta	deg	5,76	5,00	30,00
alfa	deg	65,00	30,00	65,00
h1	m	5,00	5,00	5,00
h2	m	0,50	0,50	0,50
bb	m	0,18	0,15	0,40
hb	m	0,23	0,15	0,40
xb	mm	3,00	3,00	10,00

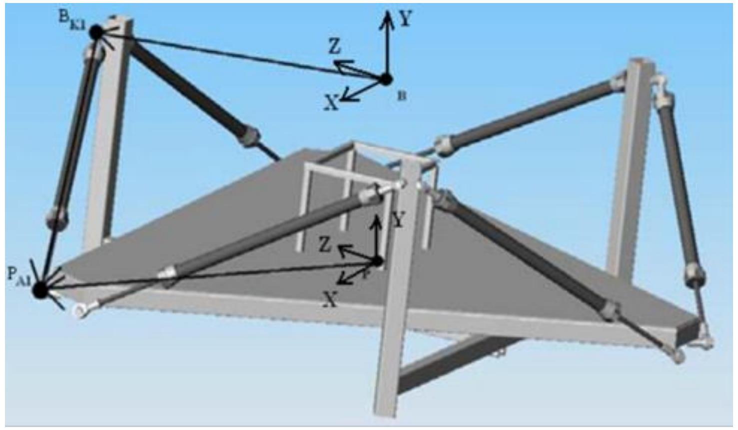
System Characteristics

Name	Units	Value	Targ. Value	Aim (sign)	Weight
L1	m	2,99	2,50	-1	20,00
L2	m	2,22	2,50	-1	1,00
M_crane	kg	100,00	100,00	-1	10,00
w	mm	4,27	20,00	-1	1,00
dt	MPa	100,58	100,00	-1	10,00
Fc	kN	50,00	50,00	-1	1,00
a	m	1,50	1,00	-1	0,00
b	m	0,46	1,00	-1	0,00

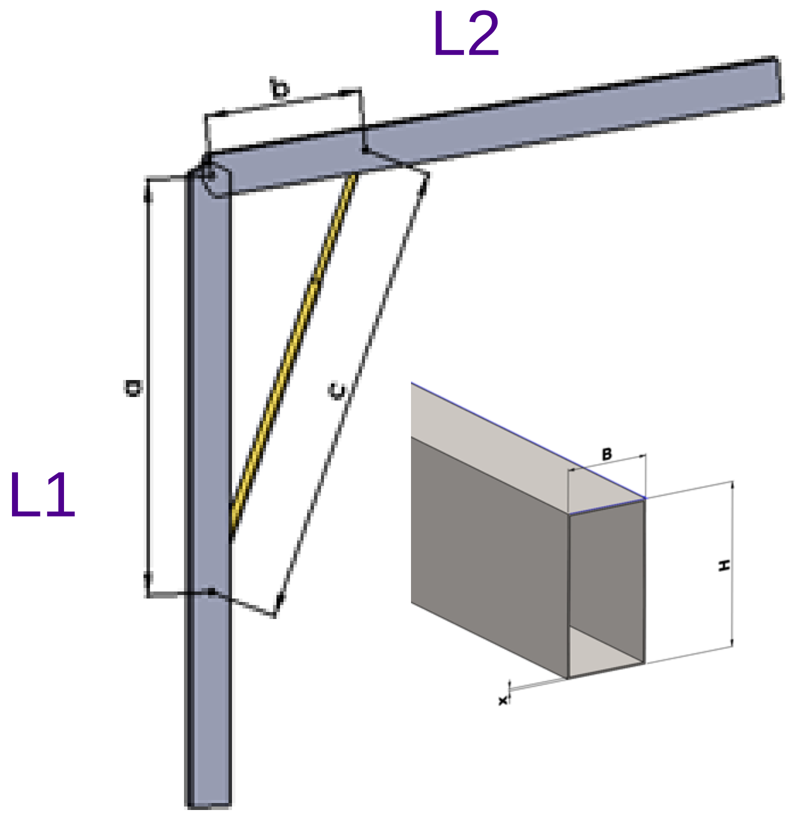
Case 1: Motion platform

Measured value		Low-fidelity model		High-fidelity model	
		Actual value	Relative error	Actual value	Relative error
a_y	3.6 m^2/s	4,37 m^2/s	21 %	3.75 m^2/s	4 %
a_x	9.0 m^2/s	12,2 m^2/s	25 %	9,45 m^2/s	6 %
ω_{max}	16 °	15,7°	2 %	16,3°	2 %

	Low-fidelity model	High-fidelity model
Number of model equations	14	30 eqs. + 58 SimMech. blocks
Number of model parameters	10	270
Time required for creation the model [h]	7	120
Time required for analyzing the model [h]	1	16
Expertise needed in modeling	Low	High



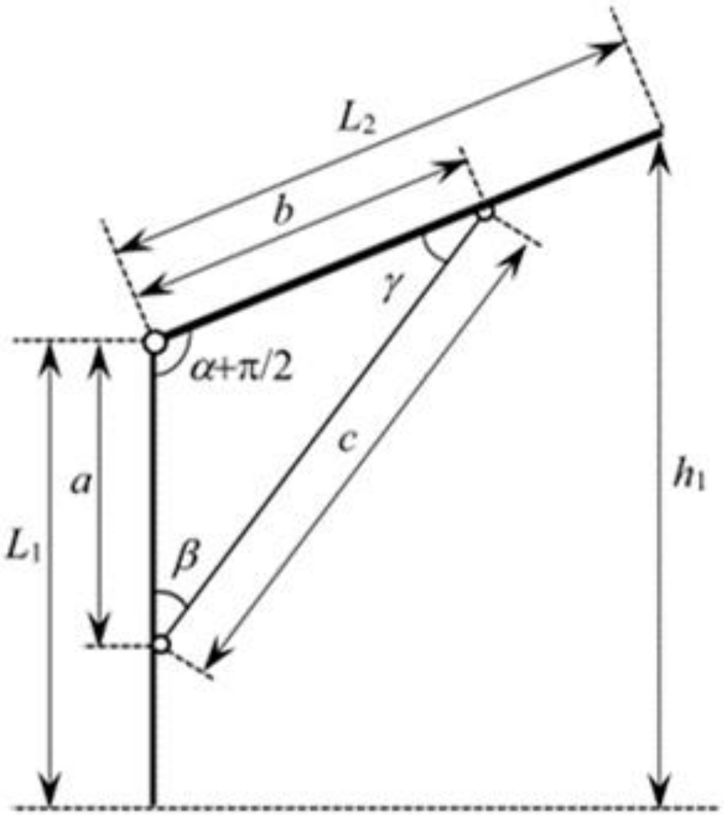
Case 2: A hydraulic crane



System characteristics

Length of beam 1 (L1)	≤ 3.0 m
Length of beam 2 (L2)	≤ 3.0 m
Mass of the crane (M_crane)	≤ 100 kg
Deflection of beam 2 (ν_{MAX})	≤ 20.0 mm
Bending stress in beam 2 (Stress)	≤ 100 MPa
Cylinder force (Fcyl)	≤ 50 kN

Case of a hydraulic crane



Design parameters

Max lifting height (h1)	5,0 m
Min lifting height (h2)	0,5 m
Max length of cylinder (c)	1,0 – 2,0 m
Angle α in max lifting state	30 – 60 deg
Angle β in max lifting state	5 – 30 deg
Width of beam (bb)	0,15 – 0,40 m
Height of beam (hb)	0,15 – 0,40 m
Sheet thickness (xb)	3 – 10 mm

Low-fidelity model

Connects design parameters to system characteristics.

12 simple equations that are based on:

- Geometry of the crane
- Statics
- Elastic bending of beam
- Total mass of the crane

Studied in upper and lower position of the crane

$$a = c\frac{\cos(\alpha+\beta)}{\cos(\alpha)}$$

$$L_2 = \frac{h_1 - h_2}{\sin(\alpha) + \left(\frac{a^2 + b^2 - \left(c/2\right)^2}{2ab}\right)}$$

$$I = \frac{BH^3 - (B-2x)(H-2x)^3}{12}$$

$$V = \frac{m_L\, g\, (L_2 - b)^3}{3EI} + \frac{m_B\, g\, (L_2 - b)^3}{8EI}$$

$$m_{TOT} = \rho_{ST}\left[BH - (B-2x)(H-2x)\right](L_1 + L_2)$$

Multi-target optimization

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Yellow fields in UI for controlling:

- Lower and upper limits for design parameters
- Target values and priorization for system characteristics

Using Excel own algoritm for optimization

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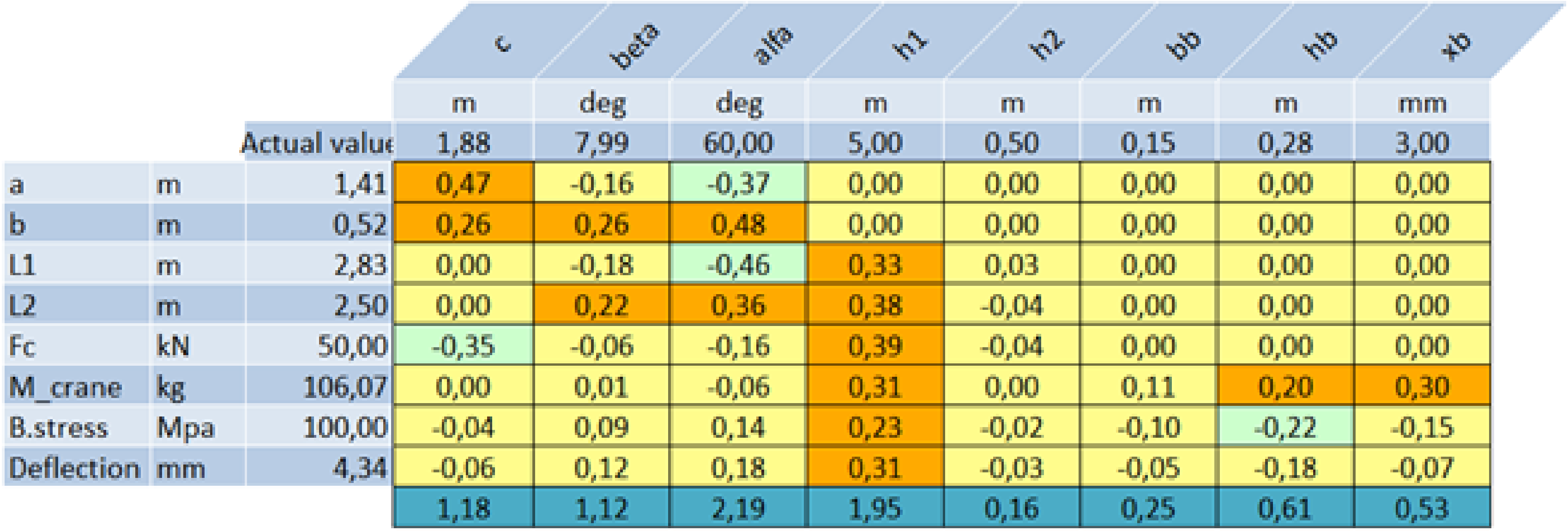
Parameter sensitivity analysis



			c	beta	alfa	h1	h2	bb	hb	xb
			m	deg	deg	m	m	m	m	mm
		Actual value	1,88	7,99	60,00	5,00	0,50	0,15	0,28	3,00
a	m	1,41	0,47	-0,16	-0,37	0,00	0,00	0,00	0,00	0,00
b	m	0,52	0,26	0,26	0,48	0,00	0,00	0,00	0,00	0,00
L1	m	2,83	0,00	-0,18	-0,46	0,33	0,03	0,00	0,00	0,00
L2	m	2,50	0,00	0,22	0,36	0,38	-0,04	0,00	0,00	0,00
Fc	kN	50,00	-0,35	-0,06	-0,16	0,39	-0,04	0,00	0,00	0,00
M_crane	kg	106,07	0,00	0,01	-0,06	0,31	0,00	0,11	0,20	0,30
B.stress	Mpa	100,00	-0,04	0,09	0,14	0,23	-0,02	-0,10	-0,22	-0,15
Deflection	mm	4,34	-0,06	0,12	0,18	0,31	-0,03	-0,05	-0,18	-0,07
			1,18	1,12	2,19	1,95	0,16	0,25	0,61	0,53

(*)System Design Parameter Priorities

Element of Jacobian matrix

$$k_{ij} = \frac{\partial y_i}{\partial x_j}$$

Dimensionless element of Jacobian matrix

$$k_{ij}^{0} = \frac{x_{s,j}}{y_{s,i}} \frac{\partial y_{s,i}}{\partial x_{s,j}}$$

$$y_0 + \Delta y = f\left(x_0\right) + J\,\Delta x \qquad \Delta \mathrm{y} = \mathrm{J}\,\Delta \mathrm{x}$$

System characteristic correlation

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Green fields in UI for controlling:

- Desired direction of a system characteristic
- -1 = low value is desired (φ)
- 1 = high value is desired (φ)

$$C_{AF,ik} = \varphi_i \varphi_k \frac{\frac{1}{n}\sum_{j=1}^{n} k_{ij}^{0} k_{kj}^{0}}{s_i s_k}$$

$$s_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n} \left(k_{ij}^{0}\right)^2}$$

System characteristic correlation

			a	b	L1	L2	Fc	M_crane	B.stress	Deflection
			m	m	m	m	kN	kg	Mpa	mm
		Actual valu	1,41	0,52	2,83	2,50	50,00	106,07	100,00	4,34
a	m	1,41	1,00	-0,25	0,54	-0,47	-0,28	0,06	-0,34	-0,43
b	m	0,52		1,00	-0,74	0,66	-0,56	-0,08	0,31	0,40
L1	m	2,83			1,00	-0,23	0,65	0,43	-0,01	-0,01
L2	m	2,50				1,00	0,25	0,36	0,68	0,86
Fc	kN	50,00					1,00	0,47	0,35	0,44
M_crane	kg	106,07						1,00	-0,19	0,12
B.stress	Mpa	100,00							1,00	0,94
Deflection	mm	4,34								1,00

System characteristics correlation matrix yields explicit information on trade-offs between system characteristics. This increases the understanding of design space

CONCLUSIONS

Low-fidelity models:

- offer fast solution to study system characteristics with an approximative (20 %) accuracy.
- can be used for requirement inspection in early system design phase.

Low-fidelity models with EDA-tool:

- enable designer to quickly study and optimize design parameters and understand nature of the system based on parameter sensitivity matrix and system characteristics correlation matrix.

REFERENCES

- A. Ellman, P. Krus, and V. Jouppila. Comparison of low- and high-fidelity approach in model based design in the case of a portable motion platform. International Conference on Engineering Design (ICED 2013), pages 227–236, 2013.
- A. Ellman, S. Pajunen, I. Laine, and E. Coatanea. Engineering design analysis tool for early design phase with low-fidelity models a case of hydraulic crane. ASME Computers and Information in Engineering Conference (IDECT/CIE 2017), 0 p., 2017.