Created in COMSOL Multiphysics 6.2

Optimization of a Crane Link Mechanism

Introduction

In complex mechanical systems, it can be challenging to find an optimal (or even good enough) solution only through engineering insight or trial-and-error procedures. Using mathematical optimization methods can then be an efficient path to a better design.

In this example, a link mechanism in a crane modeled in the Multibody Dynamics Module is optimized using the Optimization Module. The target is to reduce the cylinder force needed to carry a certain payload in a worst case operating cycle.

This example is a continuation of the model Truck Mounted Crane.

Note: This model requires the Multibody Dynamics Module and the Optimization Module.

Model Definition

The complete crane geometry is shown in Figure 1.

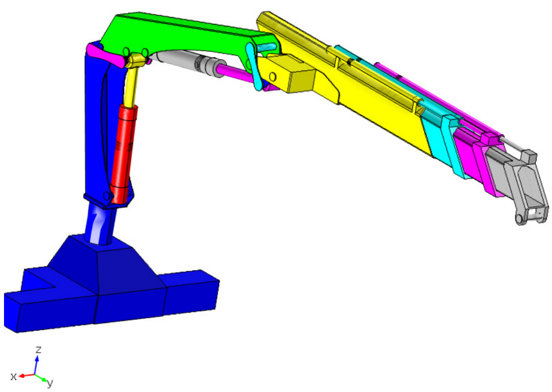

Figure 1: Crane geometry.

A close-up of the link mechanism used for controlling the inner boom is shown in Figure 2. For more details about the crane model, please refer to the description of the model Truck Mounted Crane.

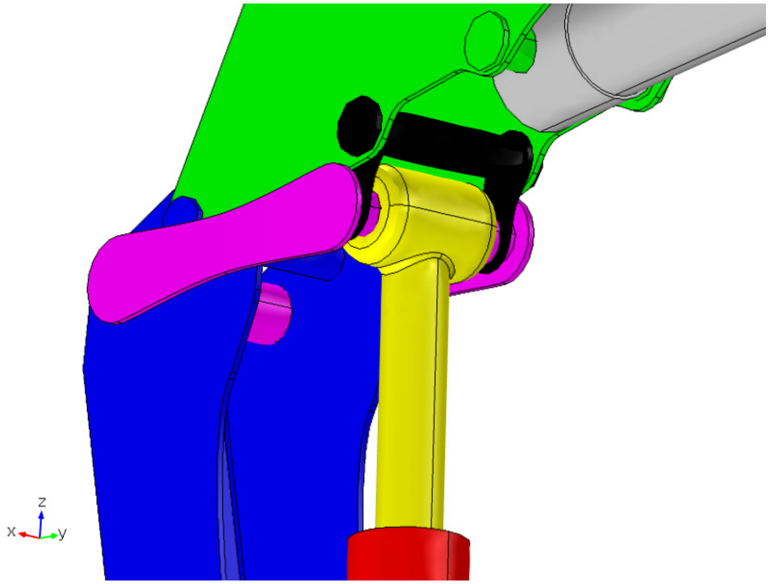

Figure 2: Close-up of link mechanisms.

A key to the coloring of the parts constituting the link mechanism is given in Table 1.

TABLE 1: IDENTIFICATION OF CRANE PARTS IN LINK MECHANISM

Part	**Name in model**	**Color in figure**
Base	Base	Blue
Inner boom	Boom1	Green
Boom lift cylinder	Cylinder1	Red
Boom lift piston	Piston1	Yellow
Link mechanism	Link1, Link2	Magenta, Black

OPERATING CYCLE

The operating cycle is selected so that the moment carried by the link mechanism is as large as possible.

- The inner boom is raised from its lowest position, 45° downward slope, to its highest position (vertical) in steps of 15°.

- The telescopic extensions are as far out as possible in all positions.
- The angle of the outer boom is chosen so that the crane tip (and thus the payload) is as far out as possible.

LOADS

- Self-weight in the negative Z direction.
- A payload of 1000 kg at the tip of the crane.

OPTIMIZATION PROBLEM

The positions of three axles can be modified, as indicated in Figure 3:

- The axle connecting the first link arm to the base.
- The axle connecting the second link arm to the boom.
- The axle connecting the two link arms and the piston of the hydraulic cylinder.

It is also necessary to ensure that the two latter axles do not move more than 10 mm closer to each other than they are in the original configuration to avoid mechanical interference.

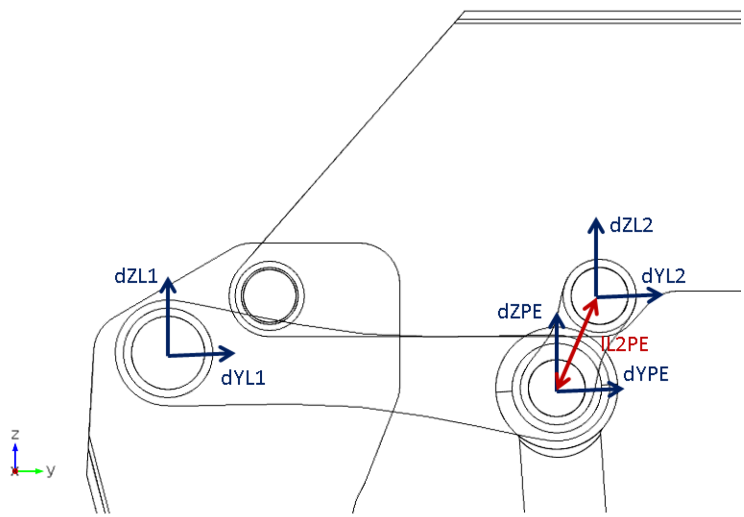

Figure 3: The optimization variables (blue) and the constraint (red).

The limits of the shifts on the axle positions are given in Table 2.

TABLE 2: ALLOWED SHIFTS IN AXLE POSITIONS

Axle	**Horizontal [mm]**	**Vertical [mm]**
Base-Link1	dYL1 = [-100, +50]	dZL1 = [-150 - +30]
Boom1-Link1	dYL2 = [-50, +50]	dZL2= [-50, +100]
Link1-Link2-Piston1	dYPE = [-50, +120]	dZPE = [-100, +20]

Results and Discussion

The force in the cylinders controlling the boom are shown in Figure 4. With the new design, it is possible to decrease the force by 31%, from 597 kN to 413 kN. This is a substantial improvement, and depending on the actual purpose of the analysis it can be utilized in two ways:

- The allowed payload can be increased. Since a significant fraction of the crane capacity is used for supporting its own weight, the increase in payload is more than 31%.
- For a constant payload, the reduced forces in the link mechanics does make it easier to reach stress and fatigue criteria for the link mechanism.

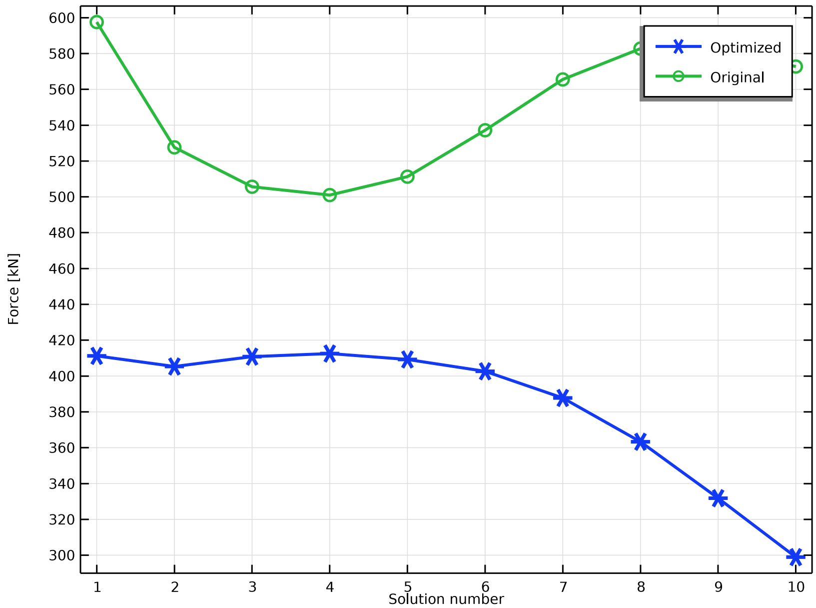

Figure 4: Variation of the cylinder force during the load cycle.

As an example of the effect of the optimization on other parts, the forces on the axle forming the hinge between the base and the boom is shown in Figure 5.

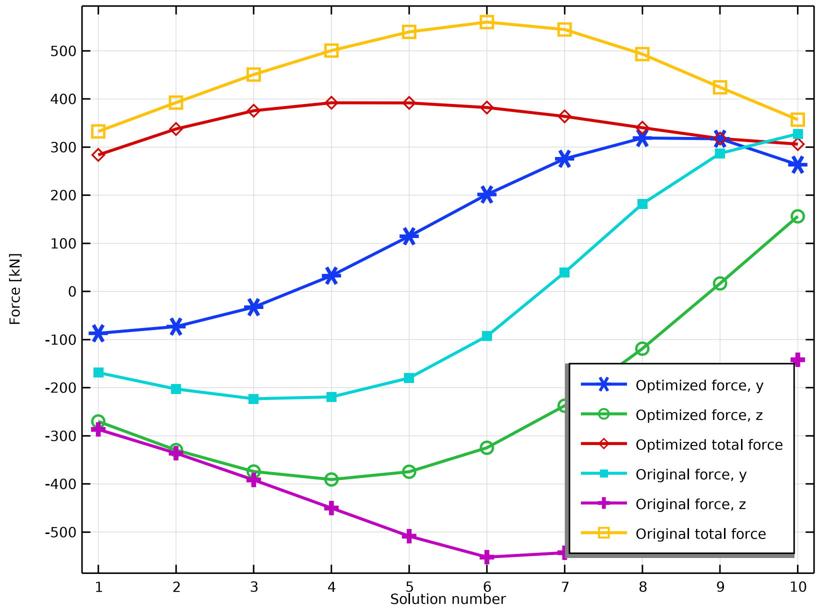

Figure 5: The forces acting on the axle between the base and the boom.

The actual values of the control variables in the optimized state may not be the same when this model is solved on different computers. The reason is that the minimum for the cylinder force can be obtained in different ways. There are multiple solutions which (within a small tolerance) give the same optimal values.

Notes About the COMSOL Implementation

Since all crane parts are rigid bodies, it is not necessary to actually move or deform the links during the optimization. It is sufficient to change the centers of the joints which mathematically represent the axles. This, however, leads to a nonintuitive graphic representation, as the links no longer rotate around the axles in the geometry.

The cylinder and piston are rotated physically in the model, since the direction of the cylinder force must be correct. Visually, the piston may look as if it was pulled out of the cylinder. This is also a graphical artifact, since another cylinder would be chosen if the modified geometry were to be selected for the final design.

In the optimization, the BOBYQA method is used. A gradient free method is suitable, since it is not possible to compute derivatives of the maximum cylinder forces with respect to the optimization parameters.

Application Library path: `Multibody_Dynamics_Module/Machinery_and_Robotics/crane_link_optimization`

Modeling Instructions

APPLICATION LIBRARIES

1 From the **File** menu, choose **Application Libraries**.

2 In the **Application Libraries** window, select **Multibody Dynamics Module>Machinery and Robotics>truck_mounted_crane** in the tree.

3 Click **Open**.

ROOT

Add the parameters needed for parameterizing the link.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `crane_link_optimization_parameters.txt`.

COMPONENT 1 (COMP1)

The cylinder and the piston must have the correct direction in order to get the correct cylinder force.

GEOMETRY 1

Rotate 1 (rot1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** node.

2 Right-click **Component 1 (comp1)>Geometry 1** and choose **Transforms>Rotate**.

3 Select the objects **imp1(31)** and **imp1(32)** only.

4 In the **Settings** window for **Rotate**, locate the **Point on Axis of Rotation** section.

5 In the **y** text field, type `YCE`.

6 In the **z** text field, type `ZCE`.

7 Locate the **Rotation** section. In the **Angle** text field, type `cylRot`.

8 From the **Axis type** list, choose **x-axis**.

MULTIBODY DYNAMICS (MBD)

In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)** node.

Hinge Joints

In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)>Hinge Joints** node.

Hinge Base-Link1

Parameterize the joint centers for the adjustable joints.

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)>Hinge Joints>Hinge Base-Link1** node, then click **Hinge Base-Link1**.

2 In the **Settings** window for **Hinge Joint**, locate the **Center of Joint** section.

3 From the list, choose **User defined**.

4 Specify the $\mathbf{X}_c$ vector as

`XC`	x
`mYL1`	y
`mZL1`	z

Hinge Boom1-Link2

1 In the **Model Builder** window, click **Hinge Boom1-Link2**.

2 In the **Settings** window for **Hinge Joint**, locate the **Center of Joint** section.

3 From the list, choose **User defined**.

4 Specify the $\mathbf{X}_c$ vector as

`XC`	x

mYL2	y
mZL2	z

Slot Link1-Link2

1 In the **Model Builder** window, expand the **Component 1 (comp1)> Multibody Dynamics (mbd)>Slot Joints** node, then click **Slot Link1-Link2**.

2 In the **Settings** window for **Slot Joint**, locate the **Center of Joint** section.

3 From the list, choose **User defined**.

4 Specify the $\mathbf{X}_c$ vector as

XC	x
mYPE	y
mZPE	z

Slot Link1-Piston1

1 In the **Model Builder** window, click **Slot Link1-Piston1**.

2 In the **Settings** window for **Slot Joint**, locate the **Center of Joint** section.

3 From the list, choose **User defined**.

4 Specify the $\mathbf{X}_c$ vector as

XC	x
mYPE	y
mZPE	z

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
ExtLen	5.5[m]	5.5 m	Total extension length

STUDY 1

Change the load cycle to a worst case scenario and compute.

Step 1: Stationary

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Study Extensions** section.

3 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Angle1 (Angle to horizontal, inner boom)	`range(-45,15,90)`	`rad`
RelAng (Angle between booms)	`0 0 0 range(0,-15,-90)`	`rad`

4 Click to select row number 3 in the table.

5 Click **Delete**.

6 In the **Home** toolbar, click **Compute**.

Save the solution for the original configuration.

Solution 1 (sol1)

In the **Model Builder** window, under **Study 1>Solver Configurations** right-click **Solution 1 (sol1)** and choose **Solution>Copy**.

RESULTS

Global 1

1 In the **Model Builder** window, expand the **Results>Boom Cylinder Forces** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 Click to select row number 2 in the table.

4 Click **Delete**.

5 In the table, enter the following settings:

Expression	Unit	Description
`abs(comp1.mbd.prj1.Fl1)`	`kN`	`Optimized`

6 Right-click **Global 1** and choose **Duplicate**.

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 - Copy 1 (sol2)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`abs(comp1.mbd.prj1.Fl1)`	`kN`	`Original`

Extension Cylinder Forces

In the **Model Builder** window, under **Results** right-click **Extension Cylinder Forces** and choose **Delete**.

Global 1

1 In the **Model Builder** window, expand the **Results>Hinge Forces** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 Click to select row number 3 in the table.

4 Click **Delete** twice.

5 In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj1.Fy`	`kN`	`Optimized force, y`
`mbd.hgj1.Fz`	`kN`	`Optimized force, z`
`sqrt(mbd.hgj1.Fy^2+ mbd.hgj1.Fz^2)`	`kN`	`Optimized total force`

6 Right-click **Global 1** and choose **Duplicate**.

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 - Copy 1 (sol2)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj1.Fy`	`kN`	`Original force, y`
`mbd.hgj1.Fz`	`kN`	`Original force, z`
`sqrt(mbd.hgj1.Fy^2+ mbd.hgj1.Fz^2)`	`kN`	`Original total force`

Add the optimization study.

STUDY 1

Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Optimization**.

2 In the **Settings** window for **Optimization**, locate the **Optimization Solver** section.

3 From the **Method** list, choose **BOBYQA**.

4 In the **Optimality tolerance** text field, type `0.1`.

5 Locate the **Objective Function** section. In the table, enter the following settings:

Expression	Description	Evaluate for
`abs(comp1.mbd.prj1.Fl1)`	`Cylinder force (inner)`	Stationary

6 From the **Solution** list, choose **Maximum of objectives**.

7 Locate the **Control Variables and Parameters** section. Click **Load from File**.

8 Browse to the model's Application Libraries folder and double-click the file `crane_link_optimization_ctrlvars.txt`.

9 Locate the **Constraints** section. In the table, enter the following settings:

Expression	Lower bound	Upper bound	Evaluate for
`mdL2PE-dL2PE`	`-0.01`		Stationary

10 Locate the **Output While Solving** section. Select the **Plot** check box.

11 From the **Plot group** list, choose **Boom Cylinder Forces**.

Avoid that the optimization loop stops in the case that a state cannot be solved.

Solution 1 (sol1)

1 In the **Model Builder** window, under **Study 1>Solver Configurations>Solution 1 (sol1)>Stationary Solver 1** click **Parametric 1**.

2 In the **Settings** window for **Parametric**, locate the **General** section.

3 From the **On error** list, choose **Store empty solution**.

Run the optimization.

4 In the **Study** toolbar, click **Compute**.

RESULTS

Boom Cylinder Forces

1 Click the **Zoom Extents** button in the **Graphics** toolbar.

2 In the **Model Builder** window, under **Results** click **Boom Cylinder Forces**.

3 In the **Boom Cylinder Forces** toolbar, click **Plot**.

Hinge Forces

1 Click the **Zoom Extents** button in the **Graphics** toolbar.

2 In the **Model Builder** window, click **Hinge Forces**.

3 In the **Hinge Forces** toolbar, click **Plot**.