Created in COMSOL Multiphysics 6.2

Dynamics of a Roller Conveyor

Introduction

Roller conveyors are commonly used in warehouses, manufacturing units and baggage handling applications to transport objects from one place to other by gravity, power, or manually. A typical roller conveyor consists of an array of moving rollers arranged either in a straight or curved manner and supported by frames. It is generally made of plastic, mild steel or stainless steel.

This model simulates the dynamics of a roller conveyor transporting a spherical object or a ball. Here, multiple cylindrical rollers are inserted between two C-sectioned beams. Cylindrical guideways are provided on both sides of the conveyor to prevent the ball falling off from rollers. The rollers are rotating about their axes, while the frames and side guideways are fixed. On reaching the other end, the ball is collected in a rectangular tray. All components of the system are assumed rigid. Using rigid body contact with friction, contact is modeled between ball and rollers, ball and side guideways, as well as ball and the surfaces of the tray. The connection between rollers and the frame is simplified using hinge joints. A transient study is performed to analyze the dynamics of ball, contact and friction forces, and energy dissipation due to friction.

Model Definition

The model geometry consists of thirty identical cylindrical rollers of outer radius 24 mm and inner radius 21 mm, and width 450 mm. The rollers are inserted between two curved C-sectioned beams of flange width 100 mm and thickness 5 mm each. The frames' web height and thickness are 40 mm and 7 mm, respectively.

A spherical ball of radius 180 mm, under the gravity load, is placed on the first roller. As shown in Figure 1, five cylindrical rods are placed as guideways on each side of the conveyor to keep the ball on the rollers by preventing falling off while moving. On reaching the other end, the ball is collected in a three-sided rectangular tray, which is kept at the far end of the conveyor. All components of the system are assumed rigid and use the material data for structural steel.

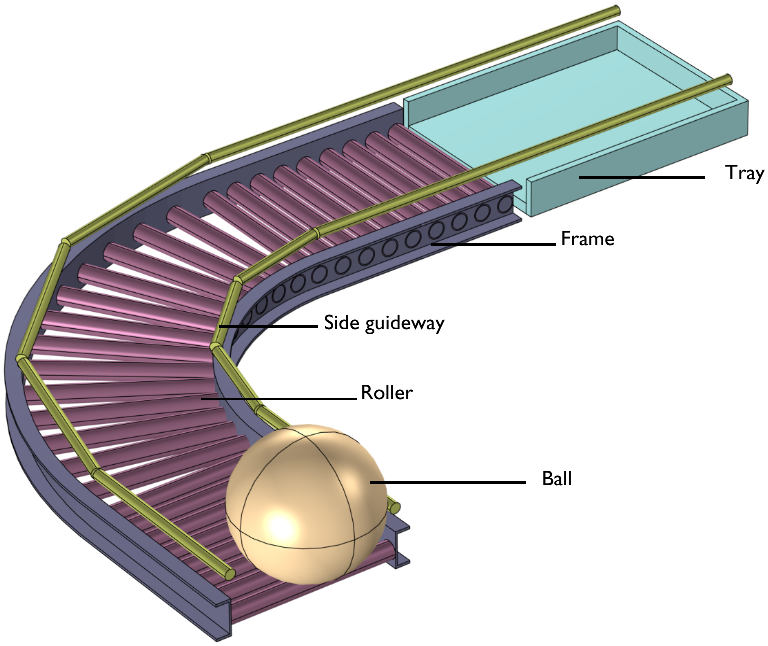

Figure 1: Model geometry of the roller conveyor.

The connections between rollers and frames are modeled through hinge joints, having only one rotational degree of freedom about their axes. The frames, guideways and tray are assumed to be fixed without any translational or rotational motion. All the rollers are rotating at an angular speed of 765 rpm.

For each rigid roller, a point of contact exists with the spherical ball. Using the rigid body contact with friction functionality, the interaction between each roller and ball is modeled as frictional contacts. The coefficient of friction between the ball and rollers is assumed as 0.1. Similar frictional contacts are used to model the interaction of the ball coming in contact with the cylindrical guideways on both sides. As the rollers rotate, the ball moves forward because of these frictional contacts and finally reaches at the end of the conveyor. Here the ball is collected in a three sided rectangular tray. Rigid body contact with friction functionality is again used to model the contact between the ball and bottom surface and far side of the tray. On the other two sides of the tray, the ball is guarded by the cylindrical guideways.

A time dependent study is performed for 8 s, to analyze the dynamics of the ball and rollers. The contact and frictional forces between ball and rollers and energy dissipation due to friction are also studied.

Results and Discussion

Figure 2 shows the displacement in the ball and rollers.

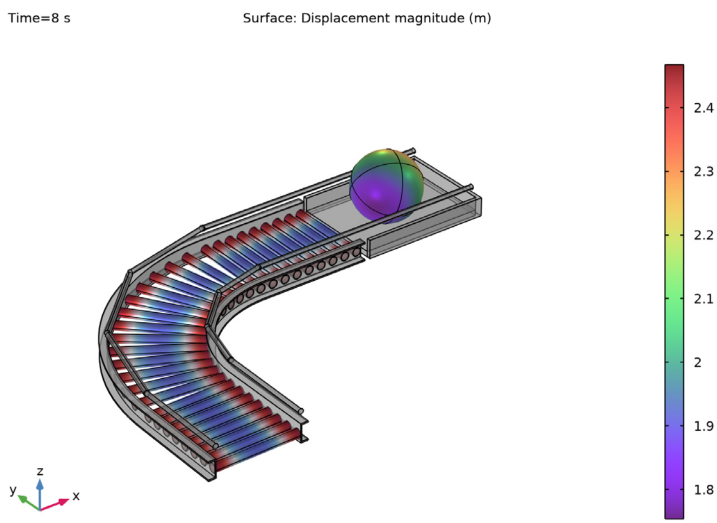

Figure 2: Displacement of different components of roller conveyor system at $t = 8$ s.

The rotation of rollers is transferred to the ball through contact between rollers and the ball. Because of frictional contact, the ball moves forward. Figure 3 and Figure 4 show the speed and angular speed of the forward moving ball, as a function of time. It is seen from these figures that as the ball moves forward, speed of the ball increases. When it reaches the tray, the speed again decreases.The components of angular velocity of the ball, as a function of time is plotted in Figure 5.

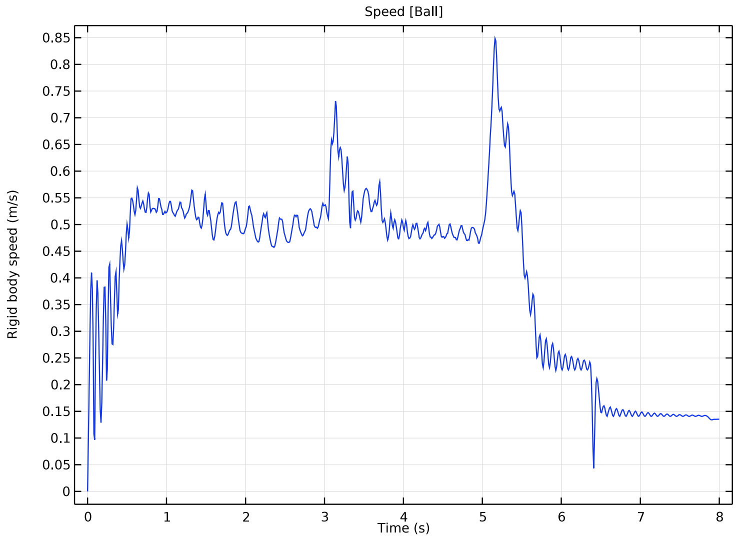

Figure 3: Speed of the ball, as a function of time.

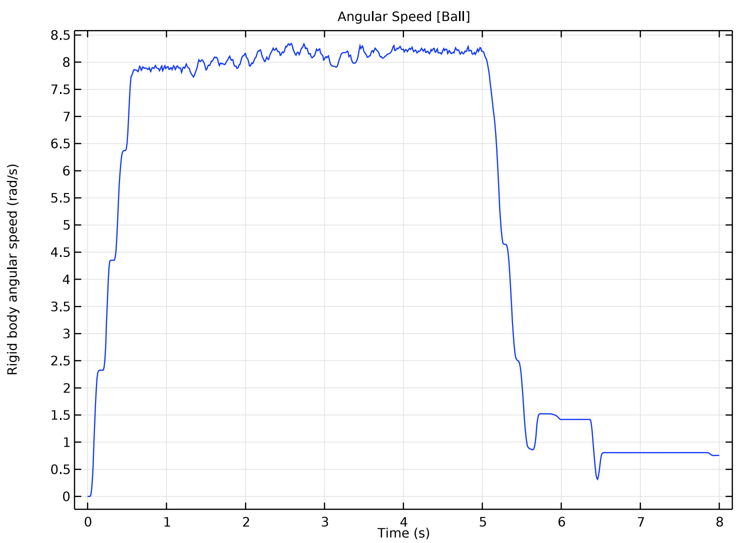

Figure 4: Angular speed of the ball, as a function of time.

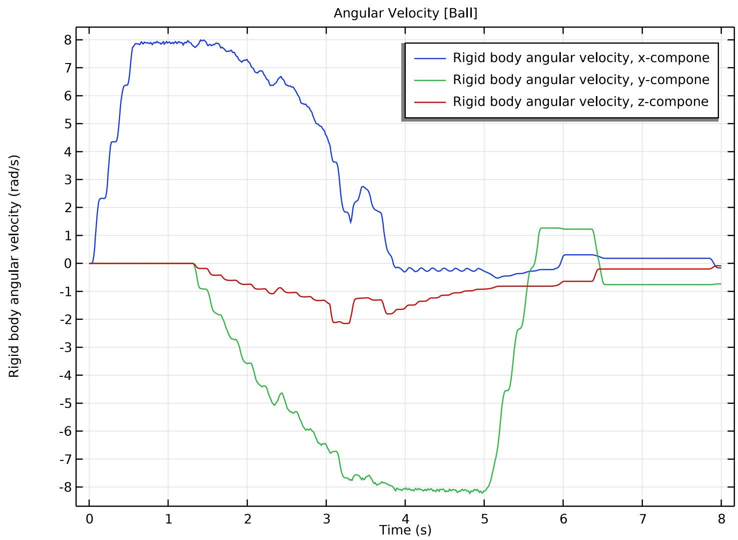

Figure 5: Angular velocity of the ball, as a function of time.

Contact and friction forces between the ball and three sample rollers are shown in Figure 6. These three sample rollers are located at the start, middle and end of the roller conveyor system.

When the ball moves forward, it comes in contact with some of the side guides also. Contact and friction forces between the ball and four sample guideways are shown in Figure 7.

Finally, when the ball falls into the tray, it starts contact with the bottom surface of the tray. While moving in the tray, the ball also comes in contact with the far side of the tray for some time. Figure 8 shows contact and friction forces between the ball and the surfaces of the tray. The ball will not touch the other two sides, as they are guarded by side guideways.

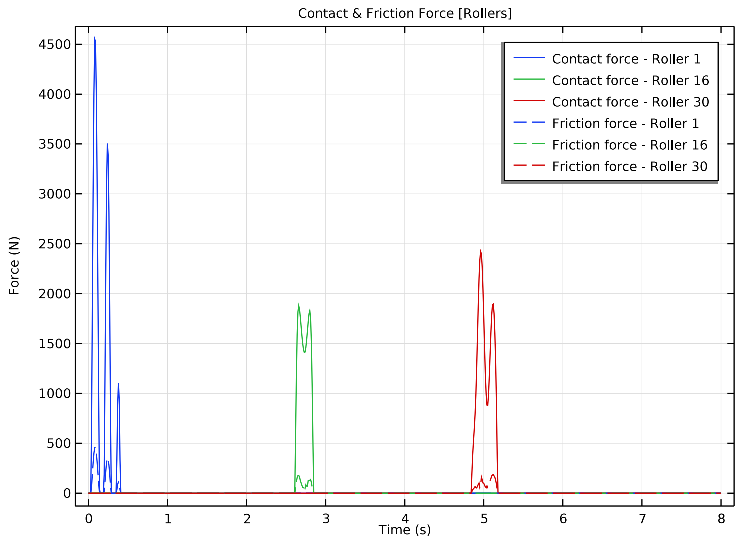

Figure 6: Contact and friction forces between the ball and three sample rollers, as a function of time.

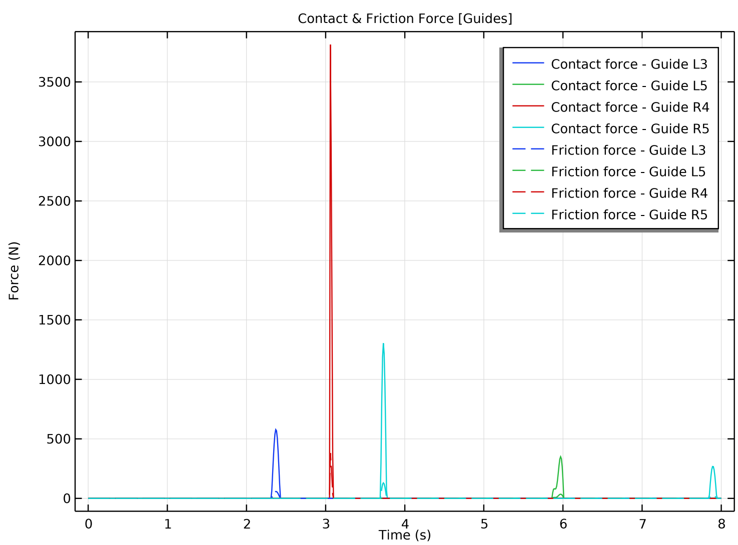

Figure 7: Contact and friction forces between the ball and guideways, as a function of time.

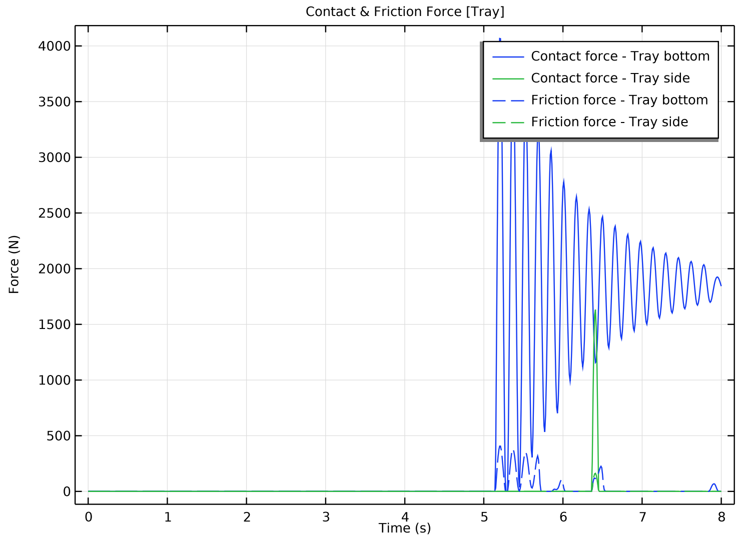

Figure 8: Contact and friction forces between the ball and the tray surfaces, as a function of time.

The frictional energy dissipation rate due to the contact between the ball and the three sample rollers is shown in Figure 9. Similarly, the frictional energy dissipation rate due to the contact between the ball and the side guideways is shown in Figure 10. Figure 11 shows the frictional energy dissipation rate due to the contact between the ball and the surfaces of the tray.

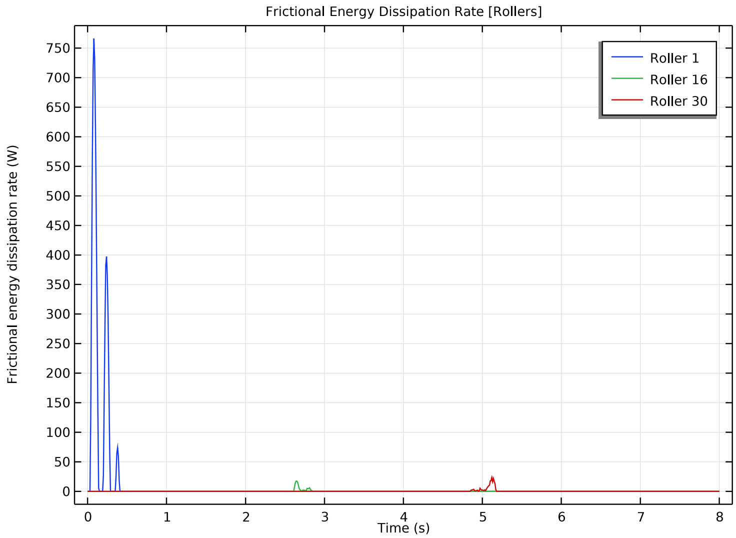

Figure 9: Frictional energy dissipation rate between the ball and three sample rollers, as a function of time.

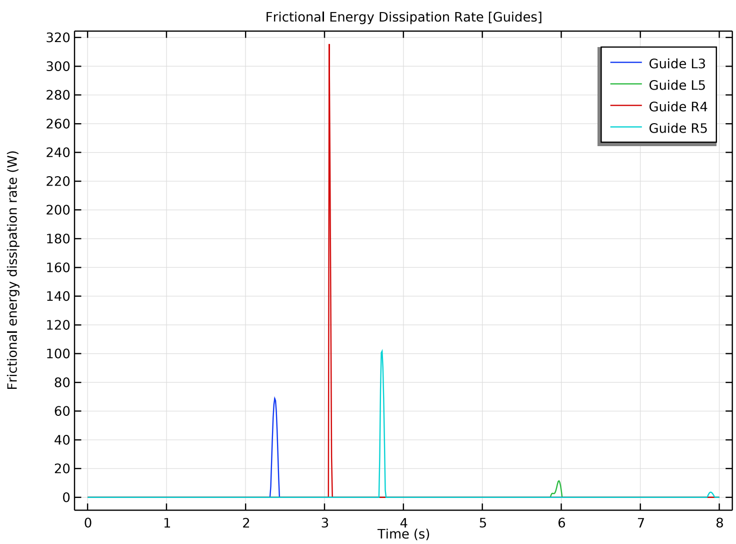

Figure 10: Frictional energy dissipation rate between the ball and guideways, as a function of time.

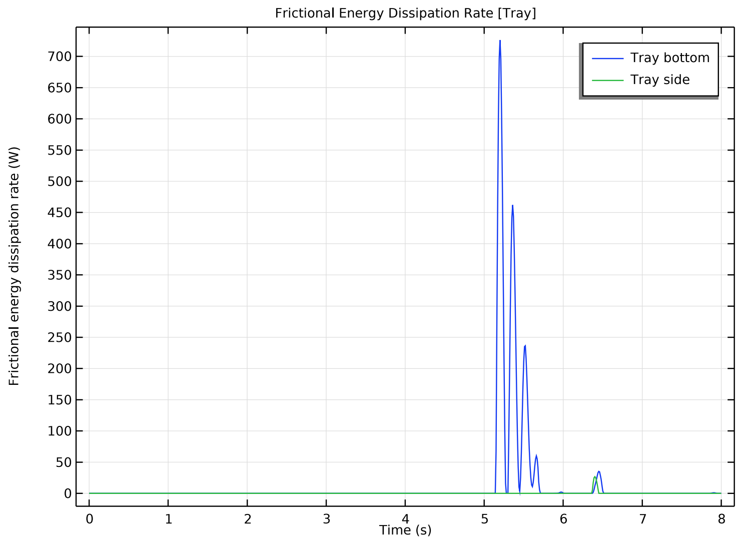

Figure 11: Frictional energy dissipation rate between the ball and tray surfaces, as a function of time.

Notes About the COMSOL Implementation

In this model, all components are modeled as rigid elements using **Rigid Material** nodes, which can be created automatically using the **Create Rigid Domains** button in the **Automated Model Setup** section in the **Settings** window for the **Multibody Dynamics** interface.

Application Library path: `Multibody_Dynamics_Module/Tutorials/roller_conveyor_dynamics`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Structural Mechanics>Multibody Dynamics (mbd)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Time Dependent**.
6 Click **Done**.

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 `roller_conveyor_dynamics_parameters.txt`.

If you do not want to import the geometry and create selections, you can load the geometry sequence from the stored model. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Geometry 1** and choose **Insert Sequence**. Browse to the model's Application Libraries folder and double-click the file `roller_conveyor_dynamics.mph`. You can then continue to the **ADD MATERIAL** section below.

To import the geometry and create selections from scratch, continue here.

GEOMETRY 1

Import 1 (imp1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Geometry 1** node.
2 Right-click **Geometry 1** and choose **Import**.
3 In the **Settings** window for **Import**, locate the **Import** section.
4 Click **Browse**.
5 Browse to the model's Application Libraries folder and double-click the file `roller_conveyor_dynamics.mphbin`.
6 Click **Import**.
7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

8 Select the **Individual object selections** check box.

9 From the **Show in physics** list, choose **All levels**.

Ball

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Ball` in the **Label** text field.

3 On the object **imp1(14)**, select Domain 1 only.

4 Locate the **Color** section. From the **Color** list, choose **None** or — if you are running the cross-platform desktop —**Custom**. On the cross-platform desktop, click the **Color** button.

5 Click **Define custom colors**.

6 Set the RGB values to 247, 213, and 164, respectively.

7 Click **Add to custom colors**.

8 Click **Show color palette only** or **OK** on the cross-platform desktop.

9 Click **Build Selected**.

Ball Boundaries

1 In the **Geometry** toolbar, click **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, type `Ball Boundaries` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Add**.

4 In the **Add** dialog box, select **Ball** in the **Input selections** list.

5 Click **OK**.

Frames

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Frames` in the **Label** text field.

3 On the object **imp1(1)**, select Domain 1 only.

4 On the object **imp1(23)**, select Domain 1 only.

5 Locate the **Color** section. From the **Color** list, choose **None** or — if you are running the cross-platform desktop —**Custom**. On the cross-platform desktop, click the **Color** button.

6 Click **Define custom colors**.

7 Set the RGB values to 100, 100, and 128, respectively.

8 Click **Add to custom colors**.

9 Click **Show color palette only** or **OK** on the cross-platform desktop.

10 Click **Build Selected**.

Guides

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Guides` in the **Label** text field.

3 On the object **imp1(17)**, select Domain 1 only.

4 On the object **imp1(2)**, select Domains 1 and 2 only.

5 On the object **imp1(22)**, select Domain 1 only.

6 On the object **imp1(25)**, select Domain 1 only.

7 On the object **imp1(26)**, select Domain 1 only.

8 On the object **imp1(29)**, select Domain 1 only.

9 On the object **imp1(3)**, select Domain 1 only.

10 On the object **imp1(33)**, select Domains 1 and 2 only.

11 Locate the **Color** section. From the **Color** list, choose **None** or — if you are running the cross-platform desktop —**Custom**. On the cross-platform desktop, click the **Color** button.

12 Click **Define custom colors**.

13 Set the RGB values to 178, 186, and 93, respectively.

14 Click **Add to custom colors**.

15 Click **Show color palette only** or **OK** on the cross-platform desktop.

16 Click **Build Selected**.

17 In the **Home** toolbar, click **Desktop Layout** and choose **Reset Desktop**.

Tray

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Tray` in the **Label** text field.

3 On the object **imp1(42)**, select Domains 1 and 2 only.

4 Locate the **Color** section. From the **Color** list, choose **None** or — if you are running the cross-platform desktop —**Custom**. On the cross-platform desktop, click the **Color** button.

5 Click **Define custom colors**.

6 Set the RGB values to 149, 200, and 200, respectively.

7 Click **Add to custom colors**.

8 Click **Show color palette only** or **OK** on the cross-platform desktop.

9 Click **Build Selected**.

Rollers

1 In the **Geometry** toolbar, click **Selections** and choose **Difference Selection**.

2 In the **Settings** window for **Difference Selection**, type `Rollers` in the **Label** text field.

3 Locate the **Input Entities** section. Click the **Add** button for **Selections to add**.

4 In the **Add** dialog box, select **Import 1** in the **Selections to add** list.

5 Click **OK**.

6 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.

7 Click the **Add** button for **Selections to subtract**.

8 In the **Add** dialog box, in the **Selections to subtract** list, choose **Ball**, **Frames**, **Guides**, and **Tray**.

9 Click **OK**.

10 In the **Settings** window for **Difference Selection**, locate the **Color** section.

11 From the **Color** list, choose **None** or — if you are running the cross-platform desktop — **Custom**. On the cross-platform desktop, click the **Color** button.

12 Click **Define custom colors**.

13 Set the RGB values to 149, 100, and 128, respectively.

14 Click **Add to custom colors**.

15 Click **Show color palette only** or **OK** on the cross-platform desktop.

16 Click **Build Selected**.

Ball Boundaries (adjsel1)

In the **Model Builder** window, right-click **Ball Boundaries (adjsel1)** and choose **Duplicate**.

Rollers Boundaries

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Ball Boundaries 1 (adjsel2)**.

2 In the **Settings** window for **Adjacent Selection**, type `Rollers Boundaries` in the **Label** text field.

3 Locate the **Input Entities** section. In the **Input selections** list, select **Ball**.

4 Click **Delete**.

5 Click **Add**.

6 In the **Add** dialog box, select **Rollers** in the **Input selections** list.

7 Click **OK**.

8 In the **Settings** window for **Adjacent Selection**, locate the **Input Entities** section.

9 In the **Input selections** list, select **Rollers**.

10 Click **Build Selected**.

Rollers (difsel1)

In the **Model Builder** window, right-click **Rollers (difsel1)** and choose **Duplicate**.

Fixed Boundaries

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Rollers 1 (difsel2)**.

2 In the **Settings** window for **Difference Selection**, type `Fixed Boundaries` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click the **Add** button for **Selections to add**.

5 In the **Add** dialog box, select **Import 1** in the **Selections to add** list.

6 Click **OK**.

7 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.

8 Click the **Add** button for **Selections to subtract**.

9 In the **Add** dialog box, in the **Selections to subtract** list, choose **Ball Boundaries** and **Rollers Boundaries**.

10 Click **OK**.

11 In the **Settings** window for **Difference Selection**, locate the **Color** section.

12 From the **Color** list, choose **None**.

13 Click **Build Selected**.

Ball (sel1), Ball Boundaries (adjsel1), Fixed Boundaries (difsel2), Frames (sel2), Guides (sel3), Rollers (difsel1), Rollers Boundaries (adjsel2), Tray (sel4)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1**, Ctrl-click to select **Ball (sel1)**, **Ball Boundaries (adjsel1)**, **Frames (sel2)**, **Guides (sel3)**, **Tray (sel4)**, **Rollers (difsel1)**, **Rollers Boundaries (adjsel2)**, and **Fixed Boundaries (difsel2)**.

2 Right-click and choose **Group**.

Selections

In the **Settings** window for **Group**, type `Selections` in the **Label** text field.

Form Union (fin)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Form Union (fin)**.
2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.
3 From the **Action** list, choose **Form an assembly**.
4 Clear the **Create pairs** check box.
5 Click **Build Selected**.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.
2 Go to the **Add Material** window.
3 In the tree, select **Built-in>Structural steel**.
4 Click **Add to Component** in the window toolbar.
5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MULTIBODY DYNAMICS (MBD)

Do as follows to generate **Rigid Material** nodes for all components.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Multibody Dynamics (mbd)**.
2 In the **Settings** window for **Multibody Dynamics**, click **Physics Node Generation** in the upper-right corner of the **Automated Model Setup** section. From the menu, choose **Create Rigid Domains**.

Rigid Material: Left Frame

1 In the **Model Builder** window, expand the **Rigid Domains (All)** node, then click **Rigid Material 1**.
2 In the **Settings** window for **Rigid Material**, type `Rigid Material: Left Frame` in the **Label** text field.

Rigid Materials

1 Similarly rename other **Rigid Material** nodes using the information given in the table below.

Rigid Material	Name
Rigid Material 1	Rigid Material: Left Frame
Rigid Material 2	Rigid Material: Guide L1

Rigid Material	**Name**
Rigid Material 3	Rigid Material: Guide R1
Rigid Material 4	Rigid Material: Guide L2
Rigid Material 5	Rigid Material: Roller 1
Rigid Material 6	Rigid Material: Roller 2
Rigid Material 7	Rigid Material: Roller 3
Rigid Material 8	Rigid Material: Roller 4
Rigid Material 9	Rigid Material: Roller 5
Rigid Material 10	Rigid Material: Roller 6
Rigid Material 11	Rigid Material: Roller 7
Rigid Material 12	Rigid Material: Roller 8
Rigid Material 13	Rigid Material: Roller 9
Rigid Material 14	Rigid Material: Roller 10
Rigid Material 15	Rigid Material: Roller 11
Rigid Material 16	Rigid Material: Roller 12
Rigid Material 17	Rigid Material: Ball
Rigid Material 18	Rigid Material: Guide L3
Rigid Material 19	Rigid Material: Roller 13
Rigid Material 20	Rigid Material: Roller 14
Rigid Material 21	Rigid Material: Roller 15
Rigid Material 22	Rigid Material: Roller 16
Rigid Material 23	Rigid Material: Guide R2
Rigid Material 24	Rigid Material: Right Frame
Rigid Material 25	Rigid Material: Roller 17
Rigid Material 26	Rigid Material: Guide L4
Rigid Material 27	Rigid Material: Guide R3
Rigid Material 28	Rigid Material: Roller 18
Rigid Material 29	Rigid Material: Roller 19
Rigid Material 30	Rigid Material: Guide R4
Rigid Material 31	Rigid Material: Roller 20
Rigid Material 32	Rigid Material: Roller 21
Rigid Material 33	Rigid Material: Roller 22
Rigid Material 34	Rigid Material: Guide R5

Rigid Material	Name
Rigid Material 35	Rigid Material: Guide L5
Rigid Material 36	Rigid Material: Roller 23
Rigid Material 37	Rigid Material: Roller 24
Rigid Material 38	Rigid Material: Roller 25
Rigid Material 39	Rigid Material: Roller 26
Rigid Material 40	Rigid Material: Roller 27
Rigid Material 41	Rigid Material: Roller 28
Rigid Material 42	Rigid Material: Roller 29
Rigid Material 43	Rigid Material: Roller 30
Rigid Material 44	Rigid Material: Tray

2 In the **Model Builder** window, click **Rigid Material: Left Frame**.

Fixed Constraint 1

In the **Physics** toolbar, click **Attributes** and choose **Fixed Constraint**.

Similarly add **Fixed Constraint** nodes to **Rigid Material: Right Frame**, **Rigid Material: Guide L1**, **Rigid Material: Guide L2**, **Rigid Material: Guide L3**, **Rigid Material: Guide L4**, **Rigid Material: Guide L5**, **Rigid Material: Guide R1**, **Rigid Material: Guide R2**, **Rigid Material: Guide R3**, **Rigid Material: Guide R4**, **Rigid Material: Guide R5** and **Rigid Material: Tray**.

Do as follows to generate **Hinge Joint** nodes between rollers and left frame.

Hinge Joint 1

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

2 In the **Settings** window for **Hinge Joint**, locate the **Attachment Selection** section.

3 From the **Source** list, choose **Rigid Material: Left Frame**.

4 From the **Destination** list, choose **Rigid Material: Roller 1**.

Center of Joint: Boundary 1

1 In the **Model Builder** window, click **Center of Joint: Boundary 1**.

2 In the **Settings** window for **Center of Joint: Boundary**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Object 4 (Import 1)**.

Hinge Joint 1

1 In the **Model Builder** window, click **Hinge Joint 1**.

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

3 From the list, choose **Select a parallel edge**.

Joint Axis 1

1 In the **Model Builder** window, click **Joint Axis 1**.

2 Select Edge 74 only.

Hinge Joint 1

In the **Model Builder** window, click **Hinge Joint 1**.

Prescribed Motion 1

1 In the **Physics** toolbar, click **Attributes** and choose **Prescribed Motion**.

2 In the **Settings** window for **Prescribed Motion**, locate the **Prescribed Rotational Motion** section.

3 From the **Prescribed motion through** list, choose **Angular velocity**.

4 In the ω_p text field, type `-omega`.

Hinge Joints

Similarly create twenty nine more **Hinge Joint** nodes between left frame and rollers by duplicating **Hinge Joint 1** and resetting the inputs using the information given in the table below.

Hinge Joint	**Source**	**Destination**	**Center of Joint: Boundary**	**Joint Axis**
Hinge Joint 1	Rigid Material: Left Frame	Rigid Material: Roller 1	29-38	74
Hinge Joint 2	Rigid Material: Left Frame	Rigid Material: Roller 2	39-48	98
Hinge Joint 3	Rigid Material: Left Frame	Rigid Material: Roller 3	49-58	122
Hinge Joint 4	Rigid Material: Left Frame	Rigid Material: Roller 4	59-68	146
Hinge Joint 5	Rigid Material: Left Frame	Rigid Material: Roller 5	69-78	170
Hinge Joint 6	Rigid Material: Left Frame	Rigid Material: Roller 6	79-88	194
Hinge Joint 7	Rigid Material: Left Frame	Rigid Material: Roller 7	89-98	218

Hinge Joint	Source	Destination	Center of Joint: Boundary	Joint Axis
Hinge Joint 8	Rigid Material: Left Frame	Rigid Material: Roller 8	99-108	242
Hinge Joint 9	Rigid Material: Left Frame	Rigid Material: Roller 9	109-118	266
Hinge Joint 10	Rigid Material: Left Frame	Rigid Material: Roller 10	119-128	290
Hinge Joint 11	Rigid Material: Left Frame	Rigid Material: Roller 11	137-146	326
Hinge Joint 12	Rigid Material: Left Frame	Rigid Material: Roller 12	147-156	350
Hinge Joint 13	Rigid Material: Left Frame	Rigid Material: Roller 13	163-172	386
Hinge Joint 14	Rigid Material: Left Frame	Rigid Material: Roller 14	173-182	410
Hinge Joint 15	Rigid Material: Left Frame	Rigid Material: Roller 15	183-192	434
Hinge Joint 16	Rigid Material: Left Frame	Rigid Material: Roller 16	193-202	458
Hinge Joint 17	Rigid Material: Left Frame	Rigid Material: Roller 17	219-228	518
Hinge Joint 18	Rigid Material: Left Frame	Rigid Material: Roller 18	241-250	566
Hinge Joint 19	Rigid Material: Left Frame	Rigid Material: Roller 19	251-260	590
Hinge Joint 20	Rigid Material: Left Frame	Rigid Material: Roller 20	267-276	626
Hinge Joint 21	Rigid Material: Left Frame	Rigid Material: Roller 21	277-286	650
Hinge Joint 22	Rigid Material: Left Frame	Rigid Material: Roller 22	287-296	677
Hinge Joint 23	Rigid Material: Left Frame	Rigid Material: Roller 23	309-318	725
Hinge Joint 24	Rigid Material: Left Frame	Rigid Material: Roller 24	319-328	749

Hinge Joint	Source	Destination	Center of Joint: Boundary	Joint Axis
Hinge Joint 25	Rigid Material: Left Frame	Rigid Material: Roller 25	329-338	773
Hinge Joint 26	Rigid Material: Left Frame	Rigid Material: Roller 26	339-348	797
Hinge Joint 27	Rigid Material: Left Frame	Rigid Material: Roller 27	349-358	821
Hinge Joint 28	Rigid Material: Left Frame	Rigid Material: Roller 28	359-368	845
Hinge Joint 29	Rigid Material: Left Frame	Rigid Material: Roller 29	369-378	869
Hinge Joint 30	Rigid Material: Left Frame	Rigid Material: Roller 30	379-388	893

In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Hinge Joint 1** to **Hinge Joint 30**. Right-click and choose **Group**.

Hinge Joints

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)** click **Group 2**.

2 In the **Settings** window for **Group**, type `Hinge Joints` in the **Label** text field.

Do as follows to generate **Rigid Body Contact** nodes between the ball and rollers.

Rigid Body Contact 1

1 In the **Physics** toolbar, click **Global** and choose **Rigid Body Contact**.

2 In the **Settings** window for **Rigid Body Contact**, locate the **Source** section.

3 From the **Source** list, choose **Rigid Material: Ball**.

4 Locate the **Destination** section. From the **Shape** list, choose **Cylindrical**.

5 From the **Destination** list, choose **Rigid Material: Roller 1**.

6 Select the **Use finite length** check box.

7 Locate the **Contact Settings** section. In the f_p text field, type `fp`.

Friction 1

1 In the **Physics** toolbar, click **Attributes** and choose **Friction**.

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

3 In the μ text field, type `mu`.

4 In the v_0 text field, type `mbd.diag*1e-3[1/s]*10`.

Ball-Rollers Contacts

1 Similarly create twenty nine more **Rigid Body Contact** nodes between the ball and rollers by duplicating **Rigid Body Contact 1** and resetting the inputs using the information given in the table below.

Name	**Source**	**Destination**
Rigid Body Contact 1	Rigid Material: Ball	Rigid Material: Roller 1
Rigid Body Contact 2	Rigid Material: Ball	Rigid Material: Roller 2
Rigid Body Contact 3	Rigid Material: Ball	Rigid Material: Roller 3
Rigid Body Contact 4	Rigid Material: Ball	Rigid Material: Roller 4
Rigid Body Contact 5	Rigid Material: Ball	Rigid Material: Roller 5
Rigid Body Contact 6	Rigid Material: Ball	Rigid Material: Roller 6
Rigid Body Contact 7	Rigid Material: Ball	Rigid Material: Roller 7
Rigid Body Contact 8	Rigid Material: Ball	Rigid Material: Roller 8
Rigid Body Contact 9	Rigid Material: Ball	Rigid Material: Roller 9
Rigid Body Contact 10	Rigid Material: Ball	Rigid Material: Roller 10
Rigid Body Contact 11	Rigid Material: Ball	Rigid Material: Roller 11
Rigid Body Contact 12	Rigid Material: Ball	Rigid Material: Roller 12
Rigid Body Contact 13	Rigid Material: Ball	Rigid Material: Roller 13
Rigid Body Contact 14	Rigid Material: Ball	Rigid Material: Roller 14
Rigid Body Contact 15	Rigid Material: Ball	Rigid Material: Roller 15
Rigid Body Contact 16	Rigid Material: Ball	Rigid Material: Roller 16
Rigid Body Contact 17	Rigid Material: Ball	Rigid Material: Roller 17
Rigid Body Contact 18	Rigid Material: Ball	Rigid Material: Roller 18
Rigid Body Contact 19	Rigid Material: Ball	Rigid Material: Roller 19
Rigid Body Contact 20	Rigid Material: Ball	Rigid Material: Roller 20
Rigid Body Contact 21	Rigid Material: Ball	Rigid Material: Roller 21
Rigid Body Contact 22	Rigid Material: Ball	Rigid Material: Roller 22
Rigid Body Contact 23	Rigid Material: Ball	Rigid Material: Roller 23
Rigid Body Contact 24	Rigid Material: Ball	Rigid Material: Roller 24
Rigid Body Contact 25	Rigid Material: Ball	Rigid Material: Roller 25
Rigid Body Contact 26	Rigid Material: Ball	Rigid Material: Roller 26
Rigid Body Contact 27	Rigid Material: Ball	Rigid Material: Roller 27
Rigid Body Contact 28	Rigid Material: Ball	Rigid Material: Roller 28

Name	Source	Destination
Rigid Body Contact 29	Rigid Material: Ball	Rigid Material: Roller 29
Rigid Body Contact 30	Rigid Material: Ball	Rigid Material: Roller 30

Add **Rigid Body Contact** nodes between the ball and side guides by duplicating **Rigid Body Contact 30** and resetting the input values.

2 Right-click **Friction 1** and choose **Duplicate**.

Rigid Body Contact 31

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)** click **Rigid Body Contact 31**.

2 In the **Settings** window for **Rigid Body Contact**, locate the **Destination** section.

3 From the **Destination** list, choose **Rigid Material: Guide L1**.

Ball-Guides Contacts

Similarly create nine more **Rigid Body Contact** nodes between the ball and side guides by duplicating **Rigid Body Contact 31** and resetting the inputs using the information given in the table below.

Name	Source	Destination
Rigid Body Contact 31	Rigid Material: Ball	Rigid Material: Guide L1
Rigid Body Contact 32	Rigid Material: Ball	Rigid Material: Guide L2
Rigid Body Contact 33	Rigid Material: Ball	Rigid Material: Guide L3
Rigid Body Contact 34	Rigid Material: Ball	Rigid Material: Guide L4
Rigid Body Contact 35	Rigid Material: Ball	Rigid Material: Guide L5
Rigid Body Contact 36	Rigid Material: Ball	Rigid Material: Guide R1
Rigid Body Contact 37	Rigid Material: Ball	Rigid Material: Guide R2
Rigid Body Contact 38	Rigid Material: Ball	Rigid Material: Guide R3
Rigid Body Contact 39	Rigid Material: Ball	Rigid Material: Guide R4
Rigid Body Contact 40	Rigid Material: Ball	Rigid Material: Guide R5

Add **Rigid Body Contact** nodes between the ball and tray surfaces by duplicating **Rigid Body Contact 40** and resetting the input values.

Rigid Body Contact 40

In the **Model Builder** window, right-click **Rigid Body Contact 40** and choose **Duplicate**.

Rigid Body Contact 41

1 In the **Model Builder** window, click **Rigid Body Contact 41**.

2 In the **Settings** window for **Rigid Body Contact**, locate the **Destination** section.

3 From the **Shape** list, choose **Planar**.

4 Locate the **Boundary Selection, Destination** section. Click to select the **Activate Selection** toggle button.

5 Select Boundary 397 only.

6 Right-click **Rigid Body Contact 41** and choose **Duplicate**.

Rigid Body Contact 42

1 In the **Model Builder** window, click **Rigid Body Contact 42**.

2 In the **Settings** window for **Rigid Body Contact**, locate the **Boundary Selection, Destination** section.

3 Click **Clear Selection**.

4 Select Boundary 403 only.

In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Rigid Body Contact 1** to **Rigid Body Contact 30**. Right-click and choose **Group**.

Ball-Rollers Contacts

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)** click **Group 3**.

2 In the **Settings** window for **Group**, type `Ball-Rollers Contacts` in the **Label** text field.

Rigid Body Contact 31, Rigid Body Contact 32, Rigid Body Contact 33, Rigid Body Contact 34, Rigid Body Contact 35, Rigid Body Contact 36, Rigid Body Contact 37, Rigid Body Contact 38, Rigid Body Contact 39, Rigid Body Contact 40

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Rigid Body Contact 31**, **Rigid Body Contact 32**, **Rigid Body Contact 33**, **Rigid Body Contact 34**, **Rigid Body Contact 35**, **Rigid Body Contact 36**, **Rigid Body Contact 37**, **Rigid Body Contact 38**, **Rigid Body Contact 39**, and **Rigid Body Contact 40**.

2 Right-click and choose **Group**.

Ball-Guides Contacts

In the **Settings** window for **Group**, type `Ball-Guides Contacts` in the **Label** text field.

Rigid Body Contact 41, Rigid Body Contact 42

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Rigid Body Contact 41** and **Rigid Body Contact 42**.

2 Right-click and choose **Group**.

Ball-Tray Contacts

In the **Settings** window for **Group**, type `Ball-Tray Contacts` in the **Label** text field.

Gravity 1

In the **Physics** toolbar, click **Global** and choose **Gravity**.

MESH 1

Free Triangular 1

1 In the **Mesh** toolbar, click **More Generators** and choose **Free Triangular**.

2 In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `13, 19, 23, 29, 39, 49, 59, 69, 79, 89, 99, 109, 119, 137, 147, 157, 162, 163, 173, 183, 193, 203, 219, 229, 234, 235, 240, 241, 251, 261, 266, 267, 277, 290, 297, 302, 312, 322, 332, 342, 352, 362, 372, 382` in the **Selection** text field.

5 Click **OK**.

Size 1

1 Right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Finer**.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Finer**.

Mapped 1

1 In the **Mesh** toolbar, click **More Generators** and choose **Mapped**.

2 Select Boundary 397 only.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Edges 917 and 926 only.

3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `25`.

Swept 1

1 In the **Mesh** toolbar, click **Swept**.

2 In the **Settings** window for **Swept**, locate the **Domain Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **All domains**.

5 Select Domains 1–14, 16–43, and 45 only.

Distribution 1

1 Right-click **Swept 1** and choose **Distribution**.

2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Frames**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type `50`.

Distribution 2

1 In the **Model Builder** window, right-click **Swept 1** and choose **Distribution**.

2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Guides**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type `20`.

Distribution 3

1 Right-click **Swept 1** and choose **Distribution**.

2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Rollers**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type `10`.

Free Tetrahedral 1

In the **Mesh** toolbar, click **Free Tetrahedral**.

Size 1

1 Right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Finer**.

4 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Domain**.

5 Select Domain 44 only.

Size 2

1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domain 15 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** check box. In the associated text field, type `0.03`.

8 Click **Build All**.

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,0.01,8)`.

4 Click to expand the **Results While Solving** section. Select the **Plot** check box.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, expand the **Study 1>Solver Configurations> Solution 1 (sol1)>Time-Dependent Solver 1** node, then click **Fully Coupled 1**.

4 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.

5 In the **Maximum number of iterations** text field, type `15`.

6 In the **Model Builder** window, under **Study 1>Solver Configurations>Solution 1 (sol1)** click **Time-Dependent Solver 1**.

7 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

8 From the **Steps taken by solver** list, choose **Intermediate**.

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

RESULTS

Click the **Show Grid** button in the **Graphics** toolbar.

Follow the instructions below to plot system displacement as shown in Figure 2.

Displacement (mbd)

In the **Model Builder** window, expand the **Results>Displacement (mbd)** node.

Selection 1

1 In the **Model Builder** window, expand the **Results>Displacement (mbd)>Surface** node.
2 Right-click **Surface** and choose **Selection**.
3 In the **Settings** window for **Selection**, locate the **Selection** section.
4 From the **Selection** list, choose **Ball Boundaries**.

Surface

In the **Model Builder** window, right-click **Surface** and choose **Duplicate**.

Selection 1

1 In the **Model Builder** window, expand the **Surface 2** node, then click **Selection 1**.
2 In the **Settings** window for **Selection**, locate the **Selection** section.
3 From the **Selection** list, choose **Rollers Boundaries**.

Surface 2

1 In the **Model Builder** window, click **Surface 2**.
2 In the **Settings** window for **Surface**, click to expand the **Title** section.
3 From the **Title type** list, choose **None**.
4 Locate the **Coloring and Style** section. Clear the **Color legend** check box.
5 Click **Change Color Table**.
6 In the **Color Table** dialog box, select **Wave>WaveLight** in the tree.
7 Click **OK**.
8 Right-click **Surface 2** and choose **Duplicate**.

Selection 1

1 In the **Model Builder** window, expand the **Surface 3** node, then click **Selection 1**.
2 In the **Settings** window for **Selection**, locate the **Selection** section.
3 From the **Selection** list, choose **Fixed Boundaries**.

Surface 3

1 In the **Model Builder** window, click **Surface 3**.
2 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.
3 From the **Coloring** list, choose **Uniform**.

4 From the **Color** list, choose **Gray**.

Transparency 1

1 Right-click **Surface 3** and choose **Transparency**.

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

3 In the **Displacement (mbd)** toolbar, click **Plot**.

Follow the instructions below to plot speed of the ball. The resulting plot should match the one shown in Figure 3.

Speed [Ball]

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Speed [Ball]` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

4 Locate the **Legend** section. Clear the **Show legends** check box.

Global 1

1 Right-click **Speed [Ball]** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`sqrt(mbd.rd15.u_tx^2+mbd.rd15.u_ty^2+mbd.rd15.u_tz^2)`	`m/s`	`Rigid body speed`

Speed [Ball]

1 In the **Model Builder** window, click **Speed [Ball]**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **x-axis label** check box.

4 Select the **y-axis label** check box.

5 In the **Speed [Ball]** toolbar, click **Plot**.

Follow the instructions below to plot angular speed of the ball. The resulting plot should match the one shown in Figure 4.

6 Right-click **Speed [Ball]** and choose **Duplicate**.

Angular Speed [Ball]

1 In the **Model Builder** window, under **Results** click **Speed [Ball] 1**.

2. In the **Settings** window for **1D Plot Group**, type `Angular Speed [Ball]` in the **Label** text field.
3. Locate the **Plot Settings** section. In the **y-axis label** text field, type `Rigid body angular speed (rad/s)`.

Global 1

1. In the **Model Builder** window, expand the **Angular Speed [Ball]** node, then click **Global 1**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3. In the table, enter the following settings:

Expression	Unit	Description
`sqrt(mbd.rd15.th_tx^2+ mbd.rd15.th_ty^2+ mbd.rd15.th_tz^2)`	`rad/s`	`Rigid body angular speed`

Angular Speed [Ball]

1. In the **Model Builder** window, click **Angular Speed [Ball]**.
2. In the **Angular Speed [Ball]** toolbar, click **Plot**.

   Follow the instructions below to plot angular velocity of the ball. The resulting plot should match the one shown in Figure 5.
3. Right-click **Angular Speed [Ball]** and choose **Duplicate**.

Angular Velocity [Ball]

1. In the **Model Builder** window, under **Results** click **Angular Speed [Ball] 1**.
2. In the **Settings** window for **1D Plot Group**, type `Angular Velocity [Ball]` in the **Label** text field.
3. Locate the **Plot Settings** section. In the **y-axis label** text field, type `Rigid body angular velocity (rad/s)`.
4. Locate the **Legend** section. Select the **Show legends** check box.

Global 1

1. In the **Model Builder** window, expand the **Angular Velocity [Ball]** node, then click **Global 1**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3. In the table, enter the following settings:

Expression	Unit	Description
`mbd.rd15.th_tx`	`rad/s`	`Rigid body angular velocity, x-component`

Expression	Unit	Description
mbd.rd15.th_ty	rad/s	Rigid body angular velocity, y-component
mbd.rd15.th_tz	rad/s	Rigid body angular velocity, z-component

4 In the **Angular Velocity [Ball]** toolbar, click **Plot**.

Follow the instructions below to plot contact and friction force between the ball and three sample rollers. The resulting plot should match the one shown in Figure 6.

Angular Velocity [Ball]

In the **Model Builder** window, right-click **Angular Velocity [Ball]** and choose **Duplicate**.

Contact & Friction Force [Rollers]

1 In the **Model Builder** window, under **Results** click **Angular Velocity [Ball] 1**.

2 In the **Settings** window for **1D Plot Group**, type `Contact & Friction Force [Rollers]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Contact & Friction Force [Rollers]** node, then click **Global 1**.

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
mbd.rbc1.Fn	N	Contact force
mbd.rbc16.Fn	N	Contact force
mbd.rbc30.Fn	N	Contact force

5 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
Contact force - Roller 1
Contact force - Roller 16
Contact force - Roller 30

7 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 **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc1.Ff`	`N`	`Friction force`
`mbd.rbc16.Ff`	`N`	`Friction force`
`mbd.rbc30.Ff`	`N`	`Friction force`

4 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

5 From the **Color** list, choose **Cycle (reset)**.

6 Click to expand the **Legends** section. In the table, enter the following settings:

Legends
`Friction force - Roller 1`
`Friction force - Roller 16`
`Friction force - Roller 30`

Contact & Friction Force [Rollers]

1 In the **Model Builder** window, click **Contact & Friction Force [Rollers]**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 In the **y-axis label** text field, type `Force (N)`.

4 In the **Contact & Friction Force [Rollers]** toolbar, click **Plot**.

Follow the instructions below to plot contact and friction force between the ball and four side guides. The resulting plot should match the one shown in Figure 7.

5 Right-click **Contact & Friction Force [Rollers]** and choose **Duplicate**.

Contact & Friction Force [Guides]

1 In the **Model Builder** window, under **Results** click **Contact & Friction Force [Rollers] 1**.

2 In the **Settings** window for **1D Plot Group**, type `Contact & Friction Force [Guides]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Contact & Friction Force [Guides]** node, then click **Global 1**.

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc33.Fn`	`N`	`Contact force`
`mbd.rbc35.Fn`	`N`	`Contact force`
`mbd.rbc39.Fn`	`N`	`Contact force`
`mbd.rbc40.Fn`	`N`	`Contact force`

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

Legends
`Contact force - Guide L3`
`Contact force - Guide L5`
`Contact force - Guide R4`
`Contact force - Guide R5`

Global 2

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

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

3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc33.Ff`	`N`	`Friction force`
`mbd.rbc35.Ff`	`N`	`Friction force`
`mbd.rbc39.Ff`	`N`	`Friction force`
`mbd.rbc40.Ff`	`N`	`Friction force`

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Friction force - Guide L3`
`Friction force - Guide L5`
`Friction force - Guide R4`
`Friction force - Guide R5`

Contact & Friction Force [Guides]

1 In the **Model Builder** window, click **Contact & Friction Force [Guides]**.

2 In the **Contact & Friction Force [Guides]** toolbar, click **Plot**.

Follow the instructions below to plot contact and friction force between the ball and tray surfaces. The resulting plot should match the one shown in Figure 8.

3 Right-click **Contact & Friction Force [Guides]** and choose **Duplicate**.

Contact & Friction Force [Tray]

1 In the **Model Builder** window, under **Results** click **Contact & Friction Force [Guides] 1**.

2 In the **Settings** window for **1D Plot Group**, type `Contact & Friction Force [Tray]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Contact & Friction Force [Tray]** node, then click **Global 1**.

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc41.Fn`	`N`	`Contact force`
`mbd.rbc42.Fn`	`N`	`Contact force`

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

Legends
`Contact force - Tray bottom`
`Contact force - Tray side`

Global 2

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

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc41.Ff`	`N`	`Friction force`
`mbd.rbc42.Ff`	`N`	`Friction force`

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

Legends
`Friction force - Tray bottom`
`Friction force - Tray side`

Contact & Friction Force [Tray]

1 In the **Model Builder** window, click **Contact & Friction Force [Tray]**.

2 In the **Contact & Friction Force [Tray]** toolbar, click **Plot**.

Follow the instructions below to plot frictional energy dissipation rate between the ball and three sample rollers. The resulting plot should match the one shown in Figure 9.

3 Right-click **Contact & Friction Force [Tray]** and choose **Duplicate**.

Frictional Energy Dissipation Rate [Rollers]

1 In the **Model Builder** window, under **Results** click **Contact & Friction Force [Tray] 1**.

2 In the **Settings** window for **1D Plot Group**, type `Frictional Energy Dissipation Rate [Rollers]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Frictional Energy Dissipation Rate [Rollers]** node, then click **Global 1**.

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc1.Qf`	`W`	`Frictional energy dissipation rate`
`mbd.rbc16.Qf`	`W`	`Frictional energy dissipation rate`
`mbd.rbc30.Qf`	`W`	`Frictional energy dissipation rate`

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

Legends
`Roller 1`
`Roller 16`
`Roller 30`

Global 2

In the **Model Builder** window, right-click **Global 2** and choose **Delete**.

Frictional Energy Dissipation Rate [Rollers]

1 In the **Model Builder** window, under **Results** click **Frictional Energy Dissipation Rate [Rollers]**.
2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.
3 Clear the **y-axis label** check box.
4 In the **Frictional Energy Dissipation Rate [Rollers]** toolbar, click **Plot**.

   Follow the instructions below to plot frictional energy dissipation rate between the ball and four sample side guides. The resulting plot should match the one shown in Figure 10.

5 Right-click **Results>Frictional Energy Dissipation Rate [Rollers]** and choose **Duplicate**.

Frictional Energy Dissipation Rate [Guides]

1 In the **Model Builder** window, under **Results** click **Frictional Energy Dissipation Rate [Rollers] 1**.
2 In the **Settings** window for **1D Plot Group**, type `Frictional Energy Dissipation Rate [Guides]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Frictional Energy Dissipation Rate [Guides]** node, then click **Global 1**.
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 Click **Clear Table**.
4 In the table, enter the following settings:

Expression	Unit	Description
mbd.rbc33.Qf	W	Frictional energy dissipation rate
mbd.rbc35.Qf	W	Frictional energy dissipation rate
mbd.rbc39.Qf	W	Frictional energy dissipation rate
mbd.rbc40.Qf	W	Frictional energy dissipation rate

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

Legends
Guide L3
Guide L5
Guide R4
Guide R5

Frictional Energy Dissipation Rate [Guides]

1 In the **Model Builder** window, click **Frictional Energy Dissipation Rate [Guides]**.

2 In the **Frictional Energy Dissipation Rate [Guides]** toolbar, click **Plot**.

Follow the instructions below to plot frictional energy dissipation rate between the ball and surfaces of tray. The resulting plot should match the one shown in Figure 11.

3 Right-click **Frictional Energy Dissipation Rate [Guides]** and choose **Duplicate**.

Frictional Energy Dissipation Rate [Tray]

1 In the **Model Builder** window, under **Results** click **Frictional Energy Dissipation Rate [Guides] 1**.

2 In the **Settings** window for **1D Plot Group**, type `Frictional Energy Dissipation Rate [Tray]` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Frictional Energy Dissipation Rate [Tray]** node, then click **Global 1**.

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

3 Click **Clear Table**.

4 In the table, enter the following settings:

Expression	Unit	Description
`mbd.rbc41.Qf`	`W`	`Frictional energy dissipation rate`
`mbd.rbc42.Qf`	`W`	`Frictional energy dissipation rate`

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

Legends
`Tray bottom`
`Tray side`

Frictional Energy Dissipation Rate [Tray]

1 In the **Model Builder** window, click **Frictional Energy Dissipation Rate [Tray]**.

2 In the **Frictional Energy Dissipation Rate [Tray]** toolbar, click **Plot**.

Angular Speed [Ball], Angular Velocity [Ball], Speed [Ball]

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Speed [Ball]**, **Angular Speed [Ball]**, and **Angular Velocity [Ball]**.

2 Right-click and choose **Group**.

Speed [Ball]

In the **Settings** window for **Group**, type `Speed [Ball]` in the **Label** text field.

Contact & Friction Force [Guides], Contact & Friction Force [Rollers], Contact & Friction Force [Tray]

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Contact & Friction Force [Rollers]**, **Contact & Friction Force [Guides]**, and **Contact & Friction Force [Tray]**.
2 Right-click and choose **Group**.

Contact & Friction Forces

In the **Settings** window for **Group**, type `Contact & Friction Forces` in the **Label** text field.

Frictional Energy Dissipation Rate [Guides], Frictional Energy Dissipation Rate [Rollers], Frictional Energy Dissipation Rate [Tray]

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Frictional Energy Dissipation Rate [Rollers]**, **Frictional Energy Dissipation Rate [Guides]**, and **Frictional Energy Dissipation Rate [Tray]**.
2 Right-click and choose **Group**.

Frictional Energy Dissipation Rates

In the **Settings** window for **Group**, type `Frictional Energy Dissipation Rates` in the **Label** text field.

Finally, to generate an animation of the roller conveyor system, follow these instructions:

Displacement (mbd)

1 In the **Results** toolbar, click **Animation** and choose **Player**.
2 In the **Settings** window for **Animation**, type `Displacement (mbd)` in the **Label** text field.
3 Locate the **Frames** section. In the **Number of frames** text field, type `100`.