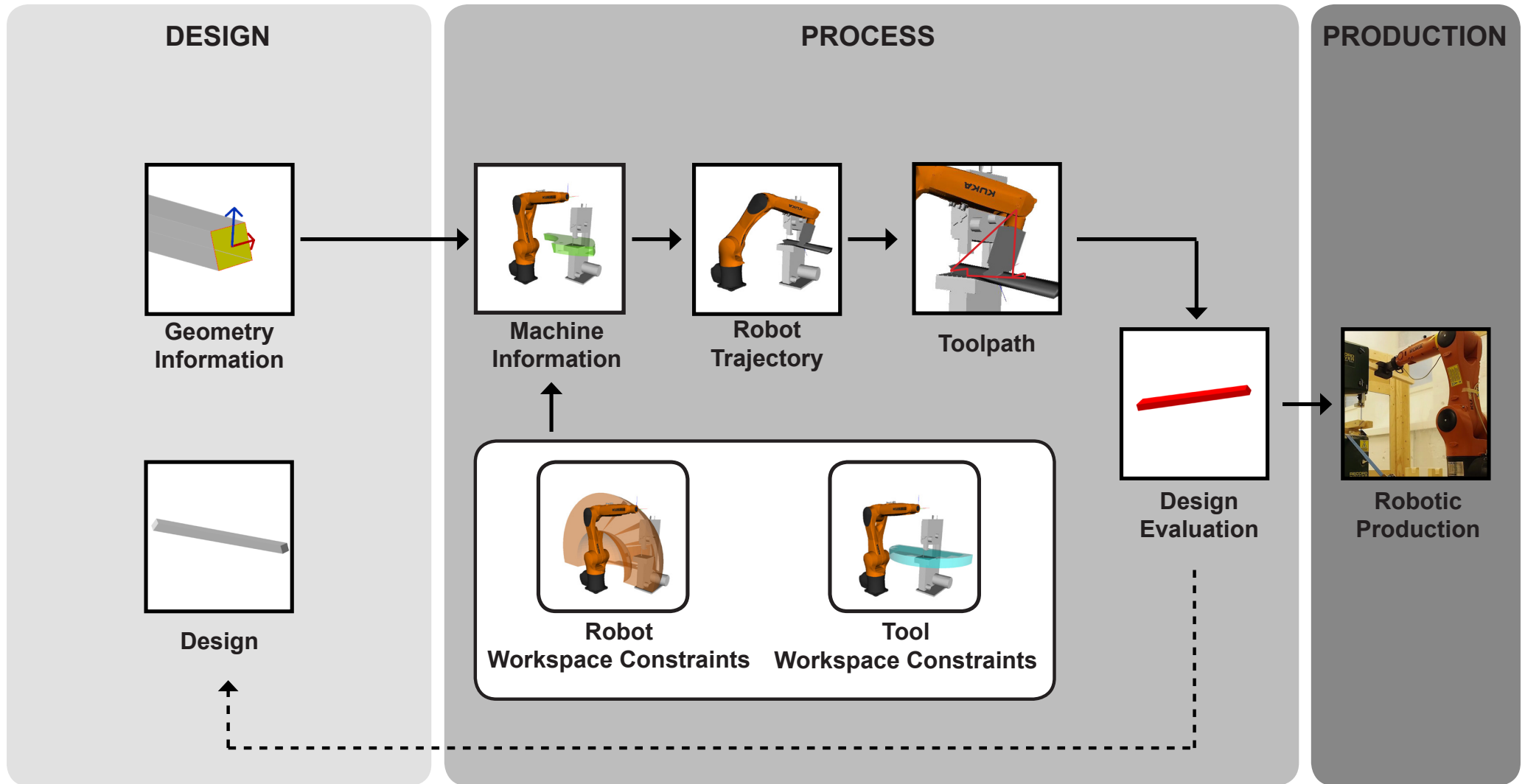


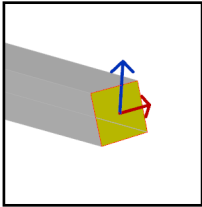
# PROCESS



---

## GEOMETRY INFORMATION

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Challenge: Geometry created in the design part not automatically provides specific geometric elements which can be used for robot tool path planning. Instead the process designer has to define the relevant geometric information and how to extracted such from the given design geometry.

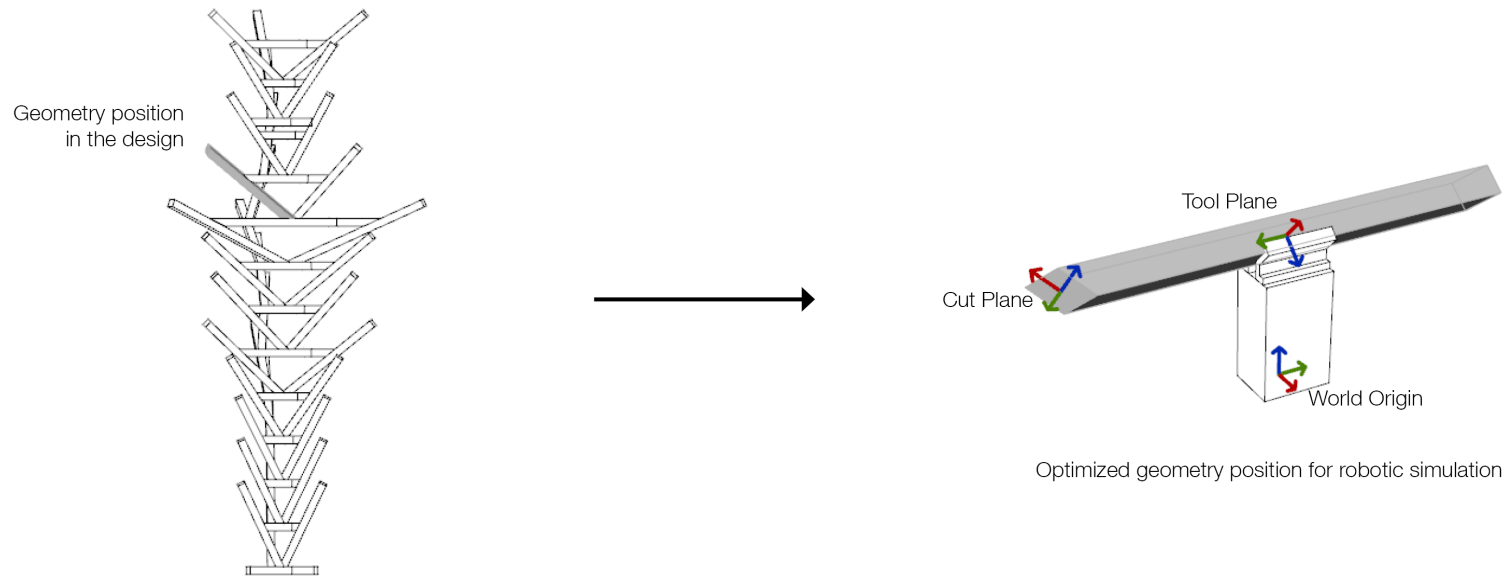
Goal: In this section you learn how to extract geometric information in form of defined planes from a given solid design geometry as basis for generating the robot tool path.

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# GEOMETRY INFORMATION

In this project, the necessary geometric information for robot tool path planning are the [1] centerline of the geometry, [2] tool plane and [3] cut plane. They are set up as following:

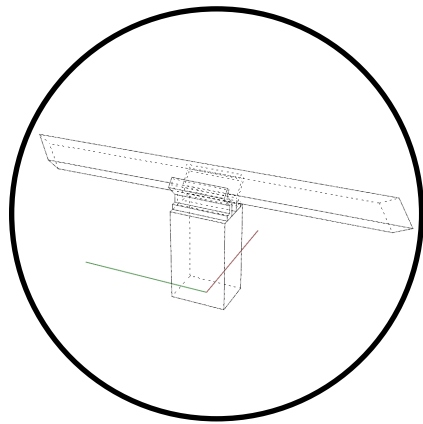
1. The centerline is extracted from the local design and follows through the longitudinal profile of the geometry. It is used as basis for the determination of tool plane and cut plane. Using the center line as basic information allows for material independent path planning. Therefore, a change of the wooden stick diameter does not effect the procedure of the robot path planning.
2. The tool plane also called geometry plane is the reference position where robot's end-effector, in this case the gripper, holds the workpiece during the fabrication process. The tool plane is generated using the center of the centerline as origin and following the centerline's orientation with the plane's y-axis. Additionally, the tool plane can be rotated around the centerline of geometry to enable suitable positioning of the gripper.
3. The cut plane is the reference plane required to position the geometry to the bandsaw blade for cutting. It is generated at the end of the centerline being also the center of the surface to be cut. The detailed orientation of this plane is described later on.



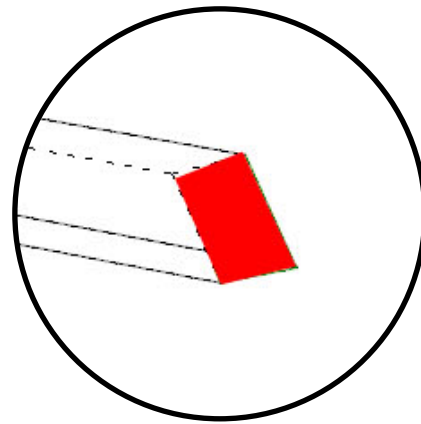
# GEOMETRY INFORMATION

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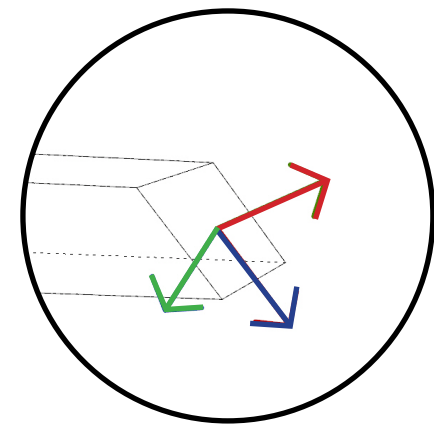
The main geometry information to be extracted necessary for the robotic simulation are the toolplane, cut plane and centerline of the geometry. The tool plane or geometry plane is the reference position where robot's end-effector, in this case the gripper, holds the workpiece during the fabrication process. A centerline is generated which follows through the longitudinal profile of the geometry, thereby independent of design and more specifically, the peripheral cuts. Hence, the tool plane can be rotated around the centerline of geometry depending on suitable position of the gripper. The cut plane is generated at center of the surface to be cut. It is the reference plane required to position the geometry to the bandsaw blade for cutting.



Orient geometry  
to tool plane



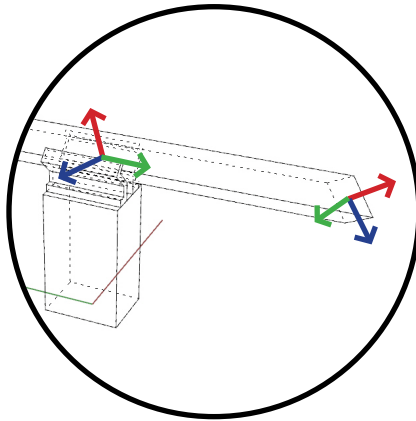
Extract surfaces to  
cut from geometry &  
select cut surface



Extract cut plane  
from cut surface & re-  
construct cut plane

# GEOMETRY INFORMATION

In order to know which geometry information needs to be extracted how, let's see which demands tool and cut plane have to full-fill to be able to interact with other planes such as the saw plane.



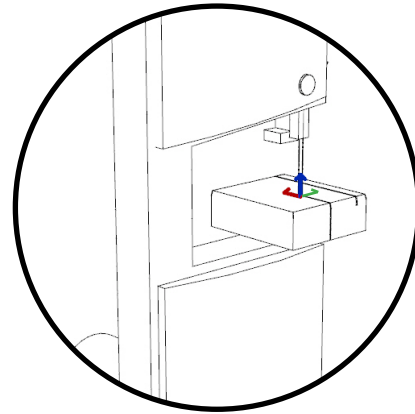
Tool Plane and Cut Plane

## Tool Plane

The tool plane is chosen freely. It is set to represent the geometries dimensions. Thereby, Y-axis is aligned to the centerline of the geometry describing its length. While x-and z-axis follow the width and the height of the geometry. The plane can be rotated around its y-axis to optimize the position of geometry within the gripper to guarantee a good cutting position.

## Cut Plane

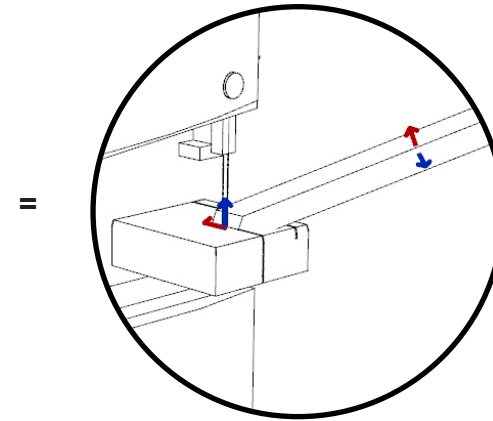
The cut plane has to be developed based on the orientation of the saw plane in order to allow for matching of both during actual cutting.



(Initial) Saw Plane

## Saw Plane

The plane at the bandsaw is chosen freely. It resembles the orientation of the bandsaw table (x- and y-axis) and cutting rod (y-axis).



Geometry Plane matching  
(initial) saw plane

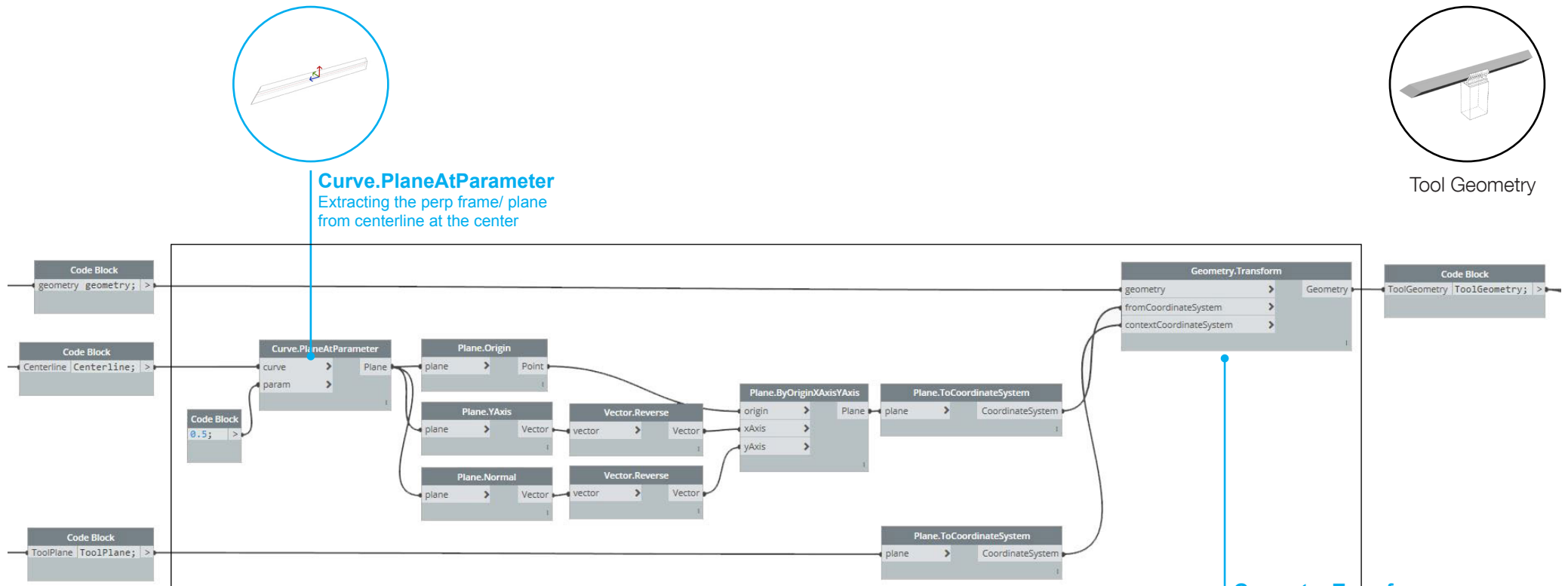
## Match cut plane and saw plane

As you have learned from the basic robotics tutorials usually the TCP (ToolCenterPoint) and the generated planes for fabrication have to match to achieve the pursued robot path planning.

In this case it is easier to imagine the cut plane matching the saw plane. The here used ToolPlane (same as TCP) is then calculated in relation to the position of this cut plane and then used for actual path planning. Therefore, the cut plane and bandsaw plane are used only as assisting geometry but not as part of a path.

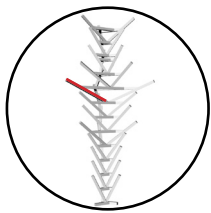
# ORIENT GEOMETRY TO TOOL PLANE

Before the geometry information is extracted, the geometry is oriented from its position in the design to geometry in tool position. This tool geometry is required for robotic simulation and to get relation of tool plane and cut plane correct.

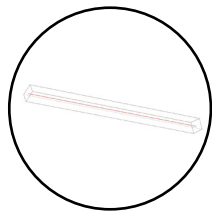


**Curve.PlaneAtParameter**  
Extracting the perp frame/ plane from centerline at the center

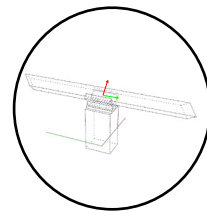
**Geometry Transform**  
Reconstruct Plane from Perpendicular Frame so the geometry aligns with the tool plane.



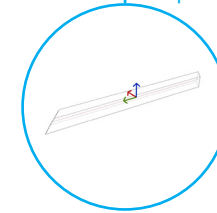
Geometry



Centerline



Tool Plane



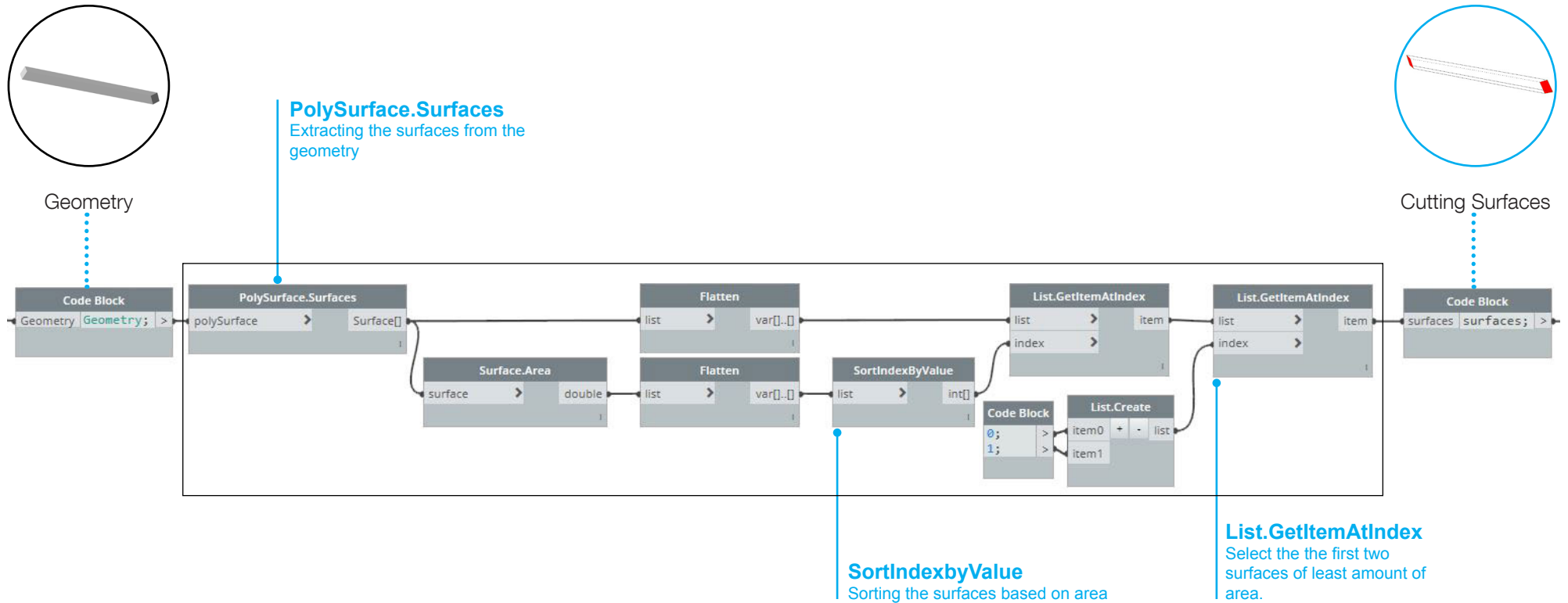
Input geometry from rhino model or select the geometry for fabrication from global design using index numbers

Input centerline from rhino model or select the geometry for fabrication from global design using index numbers

Create tool plane in Rhino model based on the tool calibration on physical robot or use provided plane.

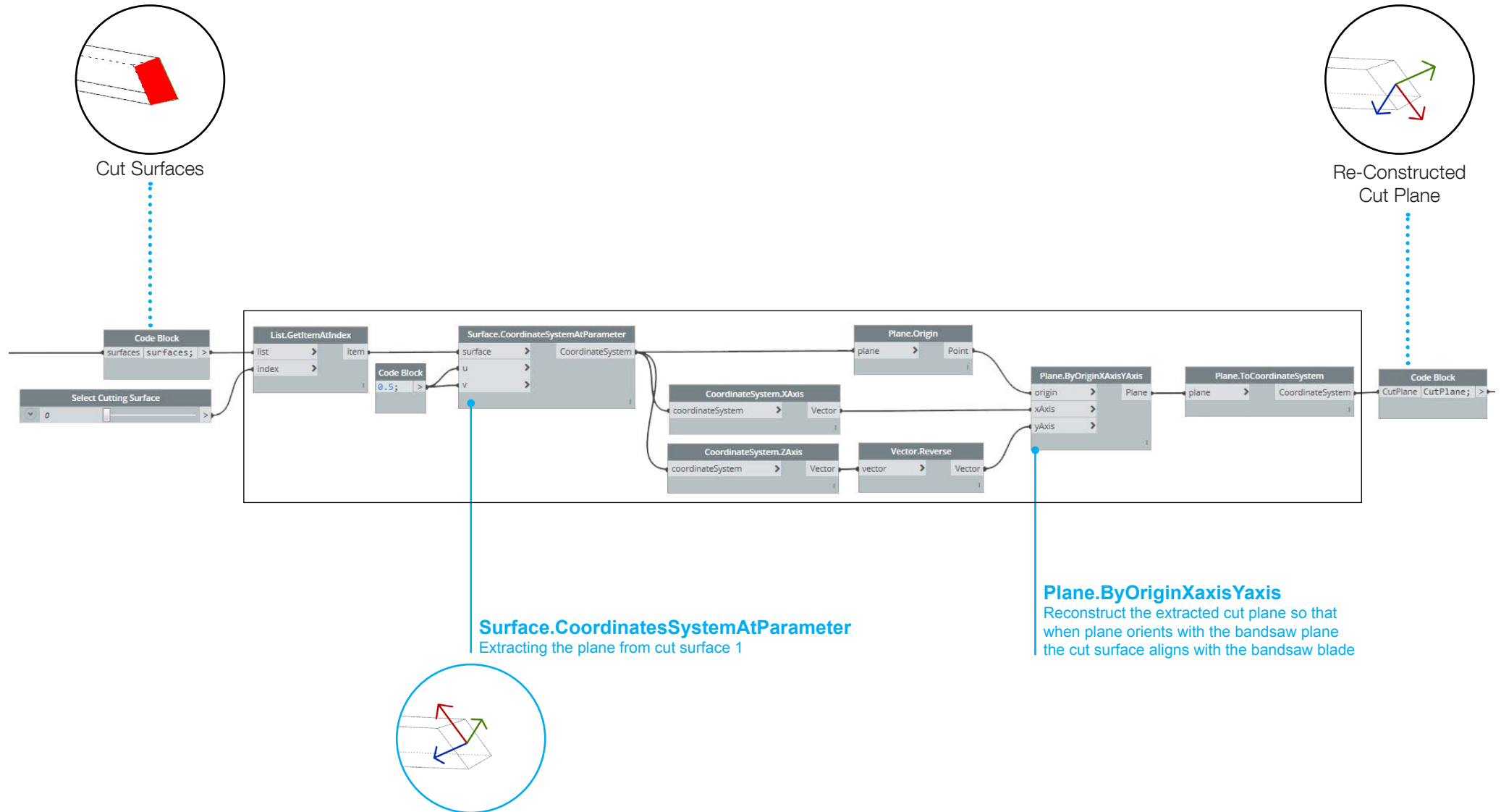
# EXTRACT SURFACES TO CUT FROM GEOMETRY & SELECT CUT SURFACE

It is always helpful to use given properties of local design logic for easy extraction of wanted elements (instead of choosing e.g. by item number of list which might change for every geometry in global design). In this case wanted surfaces are considerably smaller than other surfaces. Therefore, they can be found by comparing all surface areas of selected geometry.



# EXTRACT CUT PLANE FROM SURFACE

In order to generate the correct cut plane which later has to match with the saw plane (see description in beginning of chapter) we first need to find some way of extracting any plane from a given surface. One method is e.g. using the output of the is-planar component. But this extracted plane does not match the demands for matching the saw plane. Therefore, it needs to be reconstructed to have the x-axis and y-axis following the dimension of the surface and the y-axis pointing somewhat into the geometry.





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## MACHINE INFORMATION

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Challenge: In order to guarantee seamless production workflows the robot tool path planning can not only rely on idealized geometry based operations. Instead characteristics of the used machinery including robot and any other tool need to be analyzed for their potential to constrain robot movement.

Goal: In this section you learn how to implement relevant machine information for tool path planning.

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# MACHINE INFORMATION

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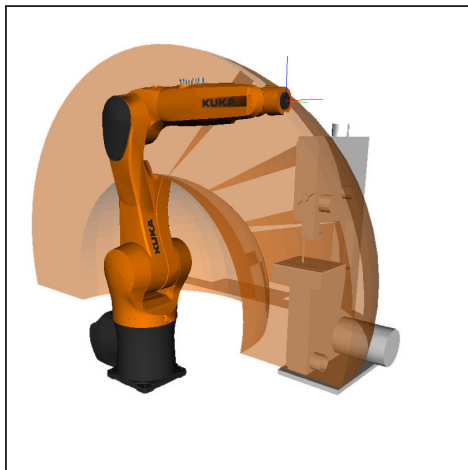
To realize the space within which fabrication can be successfully carried out we need to understand the machine workspace. The machine workspace is a combination of robot and tool workspace.

The fabrication workspace defines the manufacturability of a component which in turn defines the limits of the min/max size workpiece and min/max angle of cut.

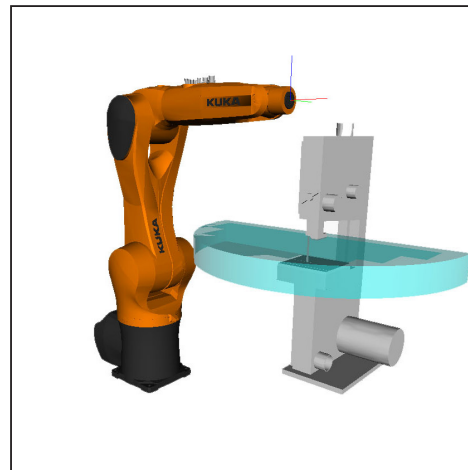
The robot workspace is the functional workspace which differs from working envelope of robot as the workspace takes into account the orientation of robot's TCP (see also Basic Robotics Movement Constraints). With the min and max reach known we can determine the three-dimensional robot workspace.

The bandsaw workspace can be described as a collection of robot's TCP positions for cutting. To determine the bandsaw workspace the timber is rotated around the bandsaw. This rotation recreates the various cutting position of timber for different angles during fabrication.

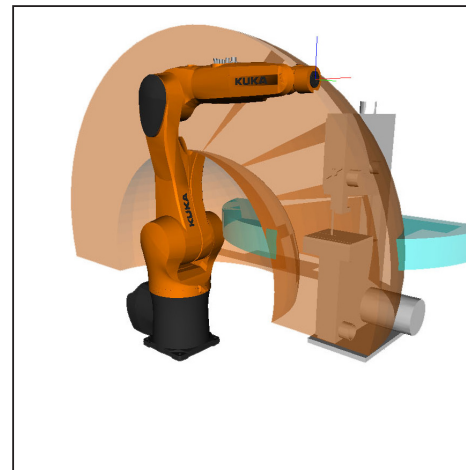
Through intersecting of robot and bandsaw workspaces, we can realize the fabrication workspace.



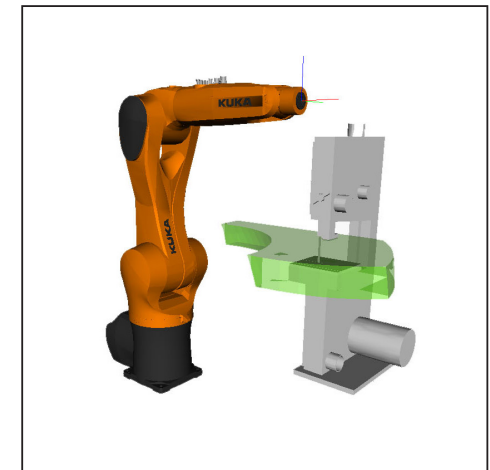
**Robot Workspace**



**Tool Workspace**



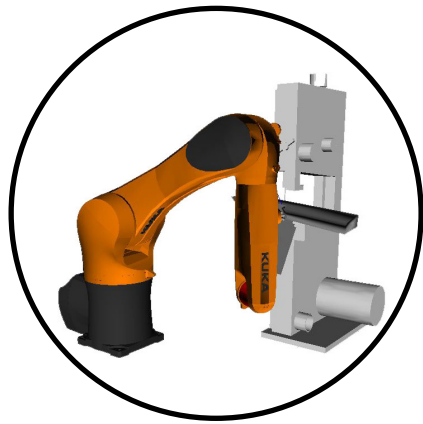
**Intersecting Workspaces**



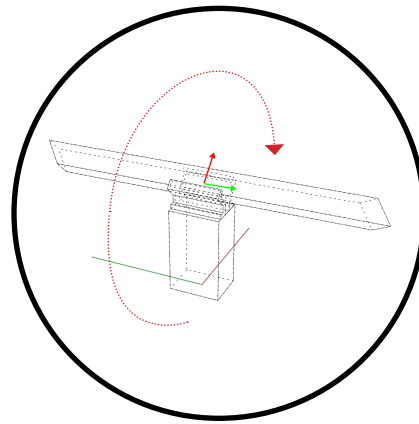
**Fabrication Workspace**

# OPITMIZE GRIPPING POSITION

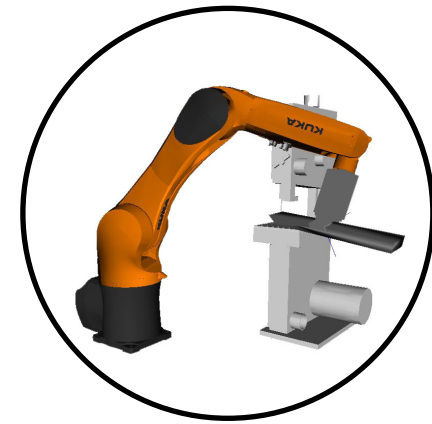
The major challenge is to orient the gripper so it can hold the timber piece from 4 directions. To avoid colision and to allow the TCP to reach its position safely, the position of the gripper is opitimized by rotating the tool plane around the centerline or the Y axis of the tool plane. As the orientation of the gripping position changes while keeping the geometry at the same position (due to its symetric cross section), the orientation of the angled surfaces at its edges dramatically changes, therefore the cut plane and thus the robot trajectory.



Robot program not executable



Optimize gripping position

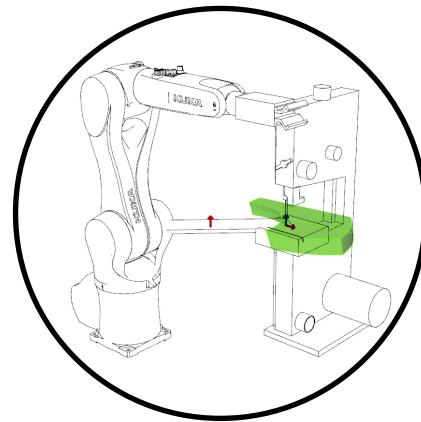


Robot program executable

# OPTIMIZED GEOMETRY POSITION TO FABRICATION WORKSPACE

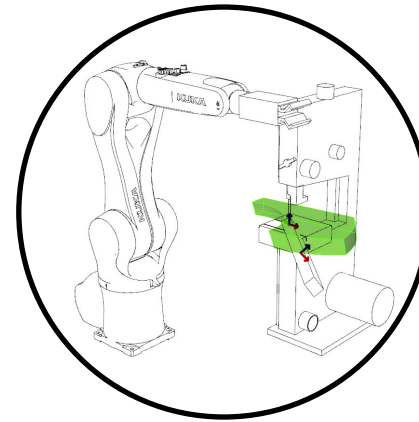
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The position of geometry and the saw plane is optimized either on front of the bandsaw or at the rear so that the geometry and the plane fall within the fabrication workspace. This is manually selected by the user by changing the bandsaw workspace input.



## Front position

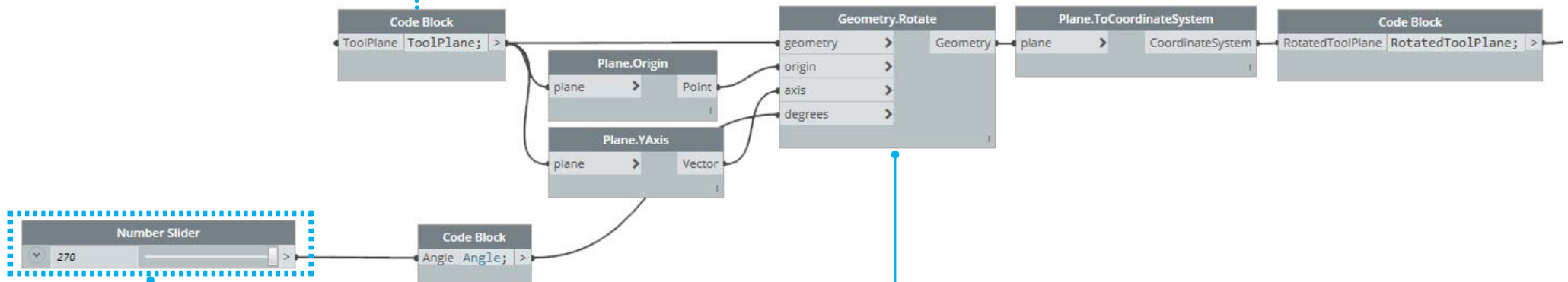
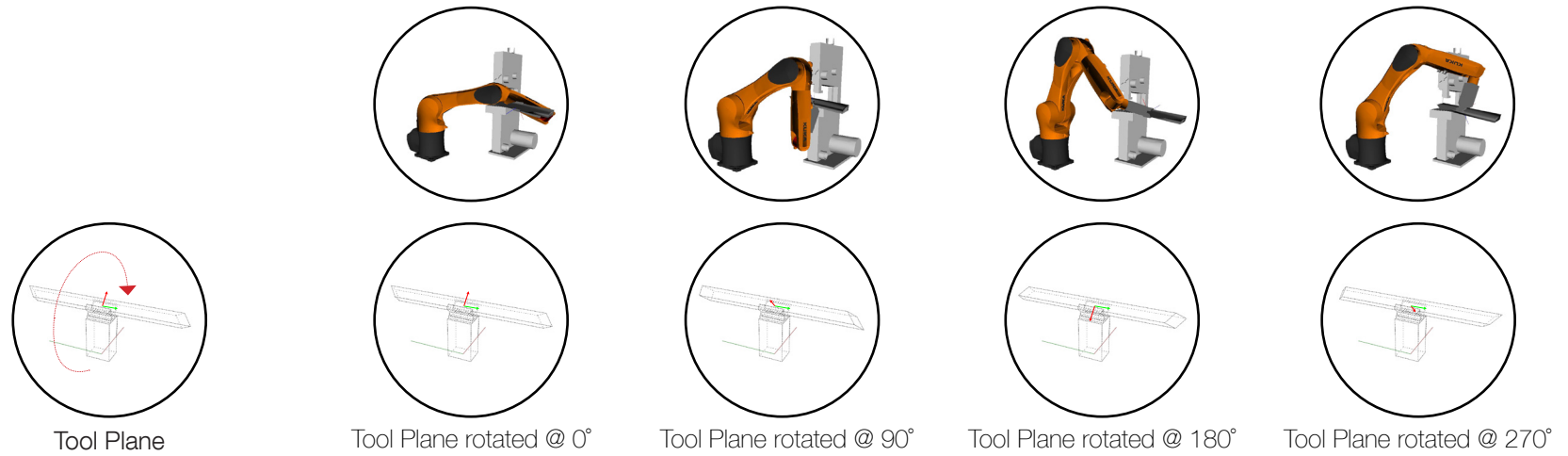
Geometry position problematic,  
tool plane not placed within the  
fabrication workspace



## Rear position

Geometry position optimized  
to place tool plane within the  
fabrication workspace

# OPITMIZE GRIPPING POSITION



## Select input

Select the rotation angle of the Tool Plane or the position in which the gripper should hold the workpiece. Use some sort of list to prepare the degrees of rotation since they are fix parameters for this process.

## Geometry.Rotate

tool plane around its own y axis to change the gripping position

---

## ROBOT TRAJECTORY

---



Challenge: To be able to create a toolpath, first positions in space (planes) need to be defined to inform the robot about where to move to later. Starting out with the preparation of the main manufacturing tool path, a fabrication plane has to be constructed defining the position of the geometry at the moment of cutting.

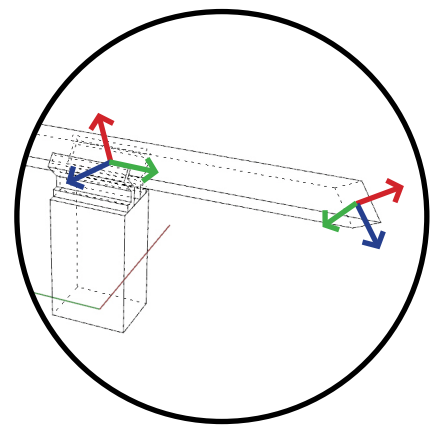
Goal: In this section you learn how to create a fabrication plane as basis for further pathplanning.

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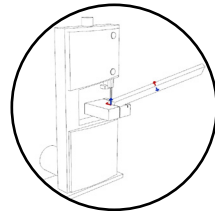
# ROBOT TRAJECTORY

As described in robot basic video about robot movement, positions in space (planes) need to be defined to inform the robot about where to move to. These planes are called robot trajectory here and are later used to generate a robot toolpath.

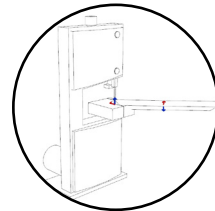
To figure out which movements and therefore which planes are necessary, the cutting process has to be analyzed: During manufacturing, various forces play a significant role which directly affects the quality of output. While manually using a bandsaw for cutting timber, majority of forces are found to be downward while cutting through the workpiece, along the blade. Generally, these forces are compensated by the machine table when workpiece rests flat or on its edge. The robot currently used in the project cannot handle heavy and high forces. Hence, the material is always required to be rested on the bandsaw table during cutting. To ensure the workpiece while cutting is always rested on its long edge or flat surface a series of steps are executed.



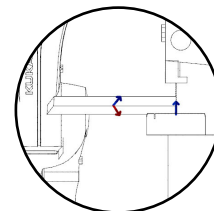
**Geometry positioned at base  
with defined  
Tool Plane and Cut Plane**



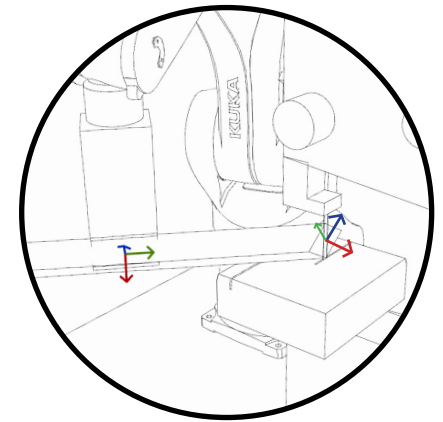
Orient cut surface  
to bandsaw blade



Align geometry  
parallel to  
bandsaw table



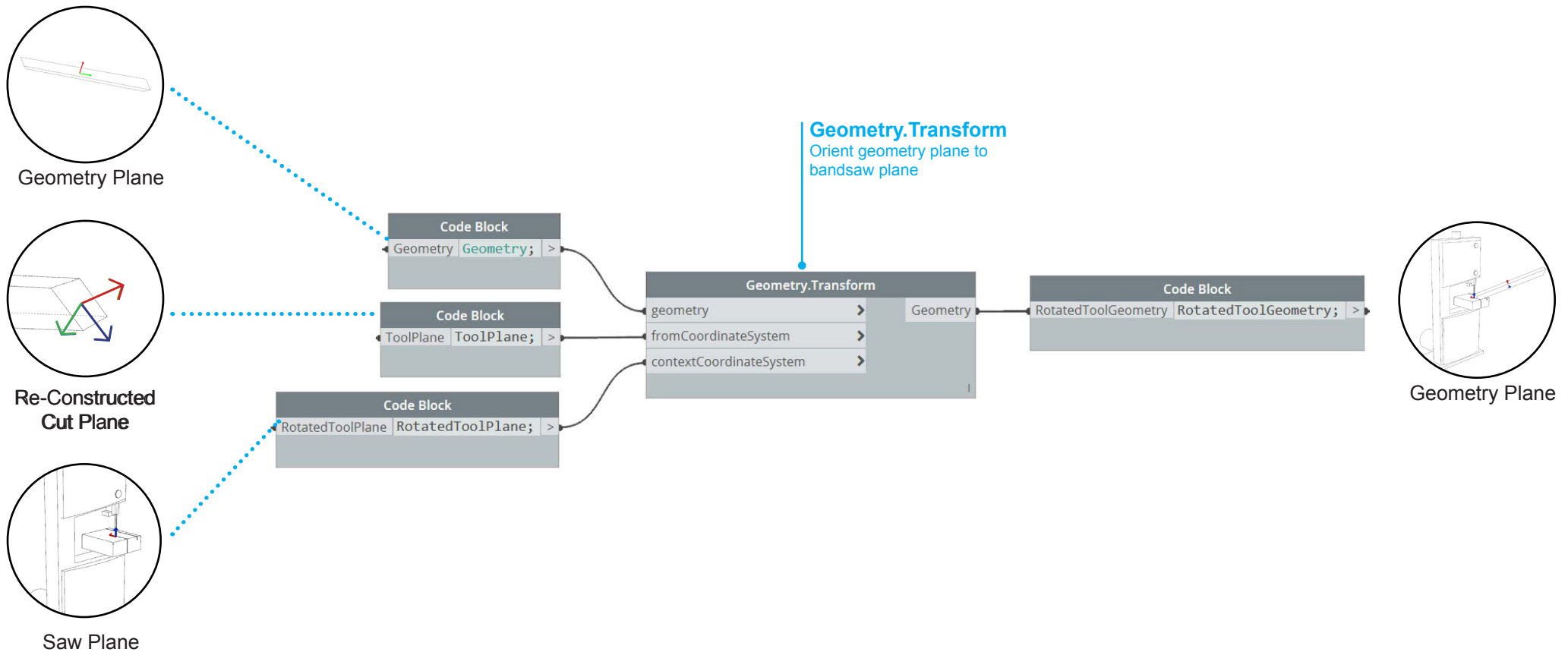
Align geometry bottom  
edge to bandsaw table for  
physical contact to table



**Final Robot Trajectory  
with cut plane matching  
optimized saw plane**

# ORIENT CUT SURFACE TO BANDSAW BLADE

First, the geometry is aligned to the bandsaw blade, so that the cut side is flat on the bandsaw blade. This orientation of the geometry plane is done by using the reconstructed cut plane to the bandsaw plane. This is an initial positioning of the geometry.

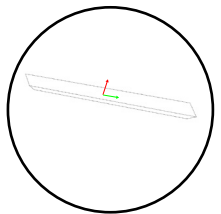
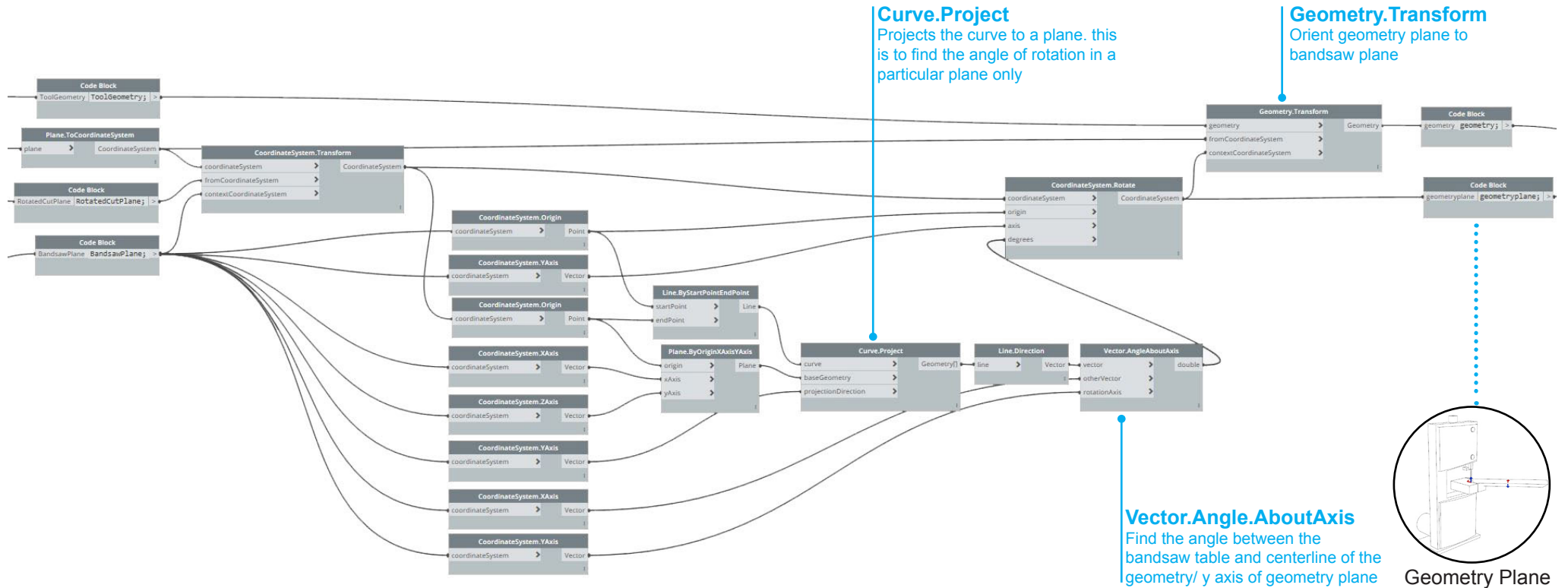


To reference the geometry and robot with respect to the bandsaw, a plane is constructed where the bandsaw blade meets the bandsaw table (see description of chapter geometry information for details).

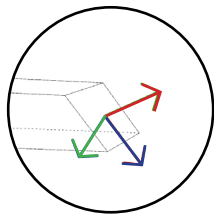


# ALIGN GEOMETRY TO BANDSAW TABLE

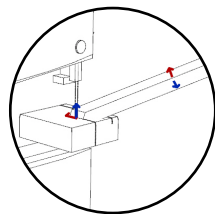
Although the surface to be cut of the geometry is aligned to the bandsaw blade the long edge/ flat surface of the workpiece is still floating in the air due to the random angle. However, to cut properly as much contact of the geometry with the bandsaw table has to be provided (see process video). To make the geometry parallel to the bandsaw table we find the difference between the normal of the surface or the Y axis of the geometry plane and X axis of the bandsaw plane.



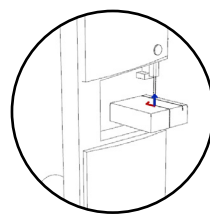
Rotated Tool Plane



Re-Constructed Cut Plane



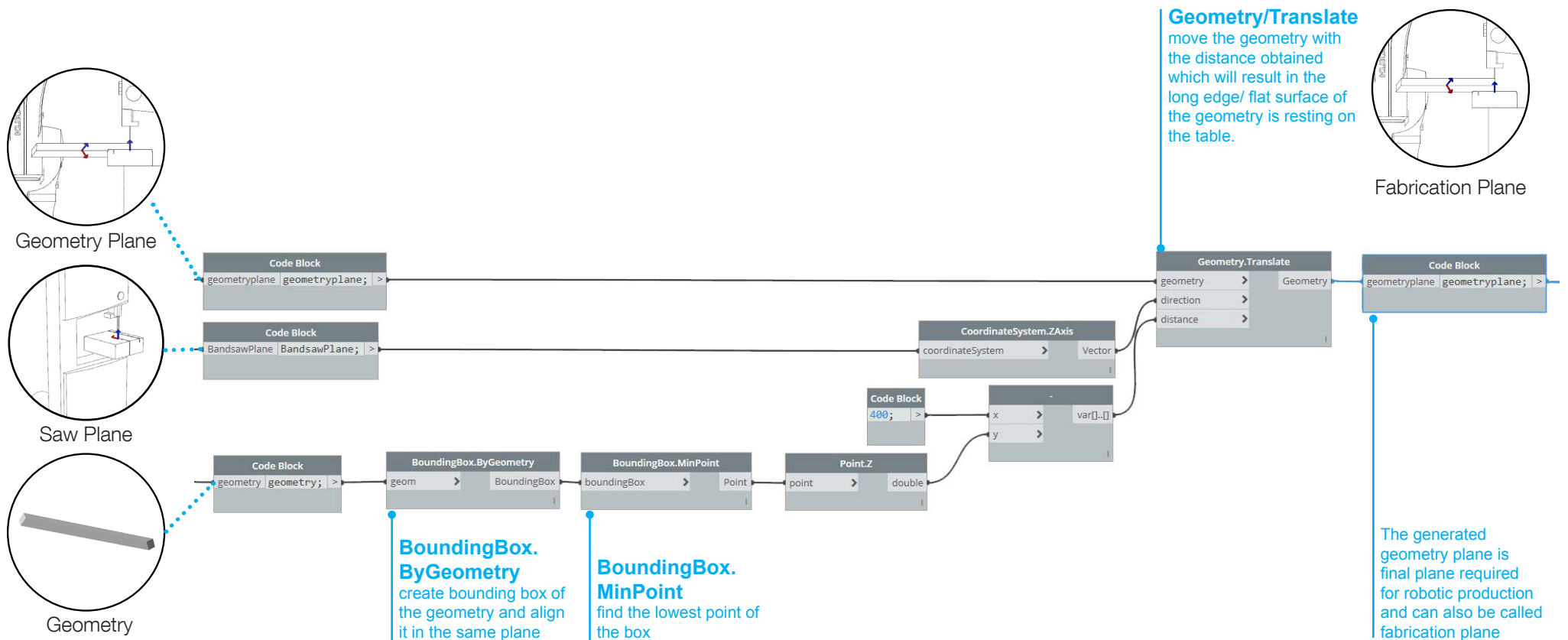
Geometry Plane



Saw Plane

# ALIGN GEOMETRY BOTTOM EDGE/ SURFACE TO BANDSAW TABLE

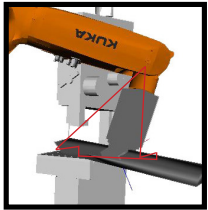
When geometry is oriented to the optimized geometry plane, the geometry is found to be colliding through the bandsaw. This is because the geometry plane is generated at the centre of the surface and is aligned to the bandsaw plane. Hence the geometry plane is required to be moved so that the geometry rests with its long edge or its flat surface on the table.



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## TOOLPATH

---



**CHALLENGE** A toolpath can not only be reduced to move to a single fabrication plane. Instead a number of tool path sequences including manufacturing movements as well as safety movements have to be designed. To generate these sequences, multiple additional planes have to be created and transferred into robot commands.

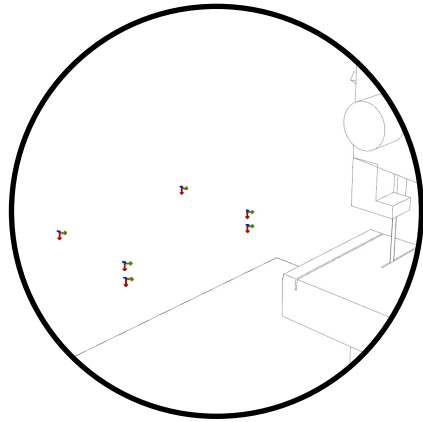
**GOAL** In this section you learn how to design a controlled, collision free tool path including manufacturing path as well as ancillary paths.

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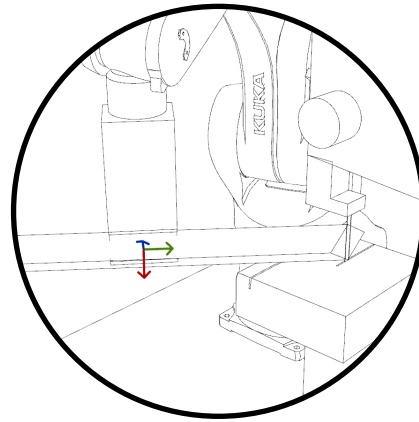
# TOOLPATH

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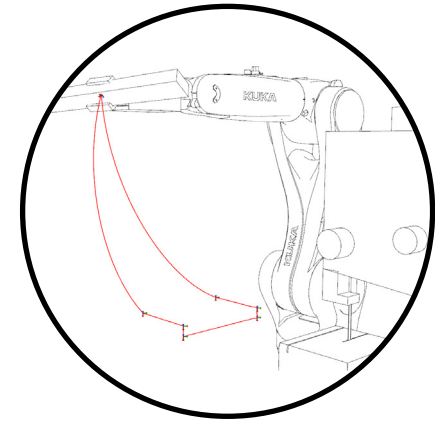
Having managed to define the robot trajectory for the cutting position now the main fabrication path as well as ancillary paths have to be planned. See Basic Robotics for information on characteristics of main manufacturing and ancillary toolpath. Firstly, the path sequence logic has to be developed (see below) afterwards necessary planes have to be created, converted into commands and merged for final toolpath creation in the algorithm.



Create Approach and  
Retract Planes



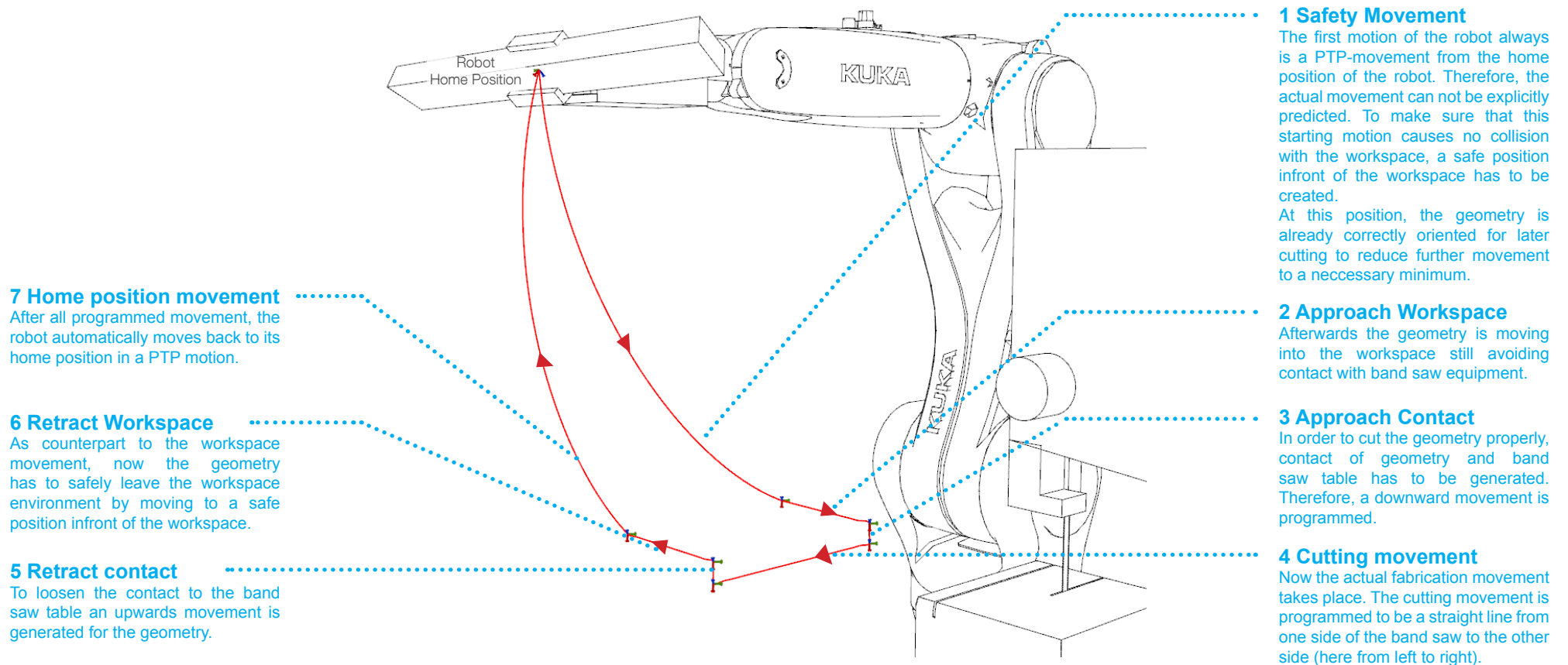
Convert Planes  
into robot  
commands



Merge commands to  
create toolpath

# TOOLPATH SEQUENCES

In order to create a controlled and collision free robot movement, the toolpath can not only consist of a cutting movement. Additional movements for approaching and retracting the work space environment in a controlled fashion have to be programmed. The approach is the safe movement of the geometry before geometry reaches the bandsaw for actual cutting. Similarly, the retract is the safe movement of geometry after the geometry has been cut. Additionally, the start and end movement of the robot to its home position (which can be set in the KUKA|prc core settings) has to be considered to guarantee smooth operation. For this particular process movements for establishing contact with the bandsaw table and to loosen this contact again have to be added to the toolpath as well.



## 7 Home position movement

After all programmed movement, the robot automatically moves back to its home position in a PTP motion.

## 6 Retract Workspace

As counterpart to the workspace movement, now the geometry has to safely leave the workspace environment by moving to a safe position in front of the workspace.

## 5 Retract contact

To loosen the contact to the band saw table an upwards movement is generated for the geometry.

## 1 Safety Movement

The first motion of the robot always is a PTP-movement from the home position of the robot. Therefore, the actual movement can not be explicitly predicted. To make sure that this starting motion causes no collision with the workspace, a safe position in front of the workspace has to be created.

At this position, the geometry is already correctly oriented for later cutting to reduce further movement to a necessary minimum.

## 2 Approach Workspace

Afterwards the geometry is moving into the workspace still avoiding contact with band saw equipment.

## 3 Approach Contact

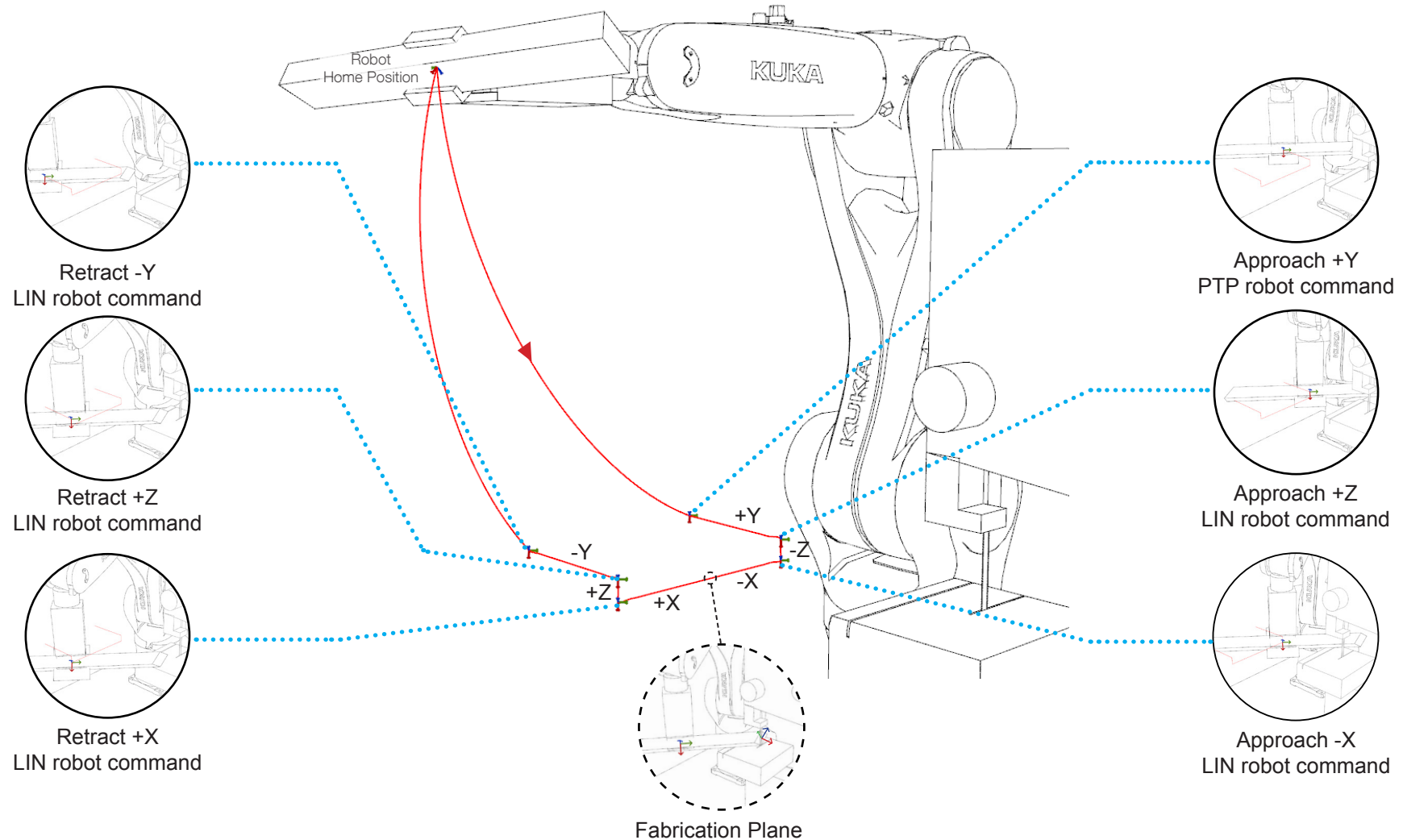
In order to cut the geometry properly, contact of geometry and band saw table has to be generated. Therefore, a downward movement is programmed.

## 4 Cutting movement

Now the actual fabrication movement takes place. The cutting movement is programmed to be a straight line from one side of the band saw to the other side (here from left to right).

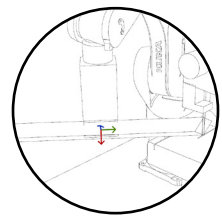
# TOOLPATH PLANE PREPARATION

To achieve the described path sequences, a number of planes have to be created to enable approach and retract movement. All these planes should be parametrically depended on each other. In this case, all approach and retract planes are depended on the fabrication plane (see robot trajectory) and are generated by moving the fabrication plane in positive or negative x,y,z directions. In the end the fabrication plane is not necessary for the actual path since two planes (approach +x and -x) already define a straight cutting movement. Additionally, for each motion sequence a suitable robot movement command (PTP or LIN) has to be chosen.

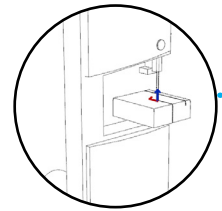


# CREATE APPROACH PLANE IN -X AXIS OF BANDSAW

The generation of all approach and retract planes follows a similar strategy. Therefore, only the algorithm for creating the -x approach is depicted. Develop similar algorithms for different approach and retracts according to the images and descriptions above.



Fabrication Plane



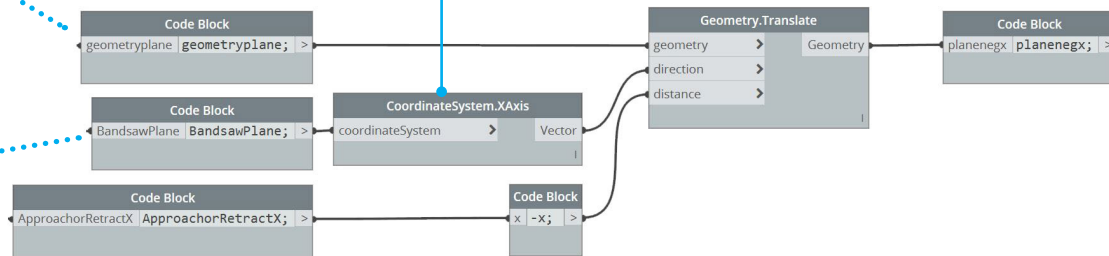
Saw Plane

## Approach and retract

the distances are adjusted by the user through careful calculation so that collisions are avoided and a successful cut is achieved.

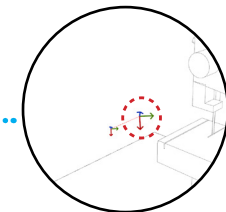
## CoordinateSystem.XAxis

Extract the appropriate vector to define in which of the three directions the fabrication plane will be moved.



## Negative

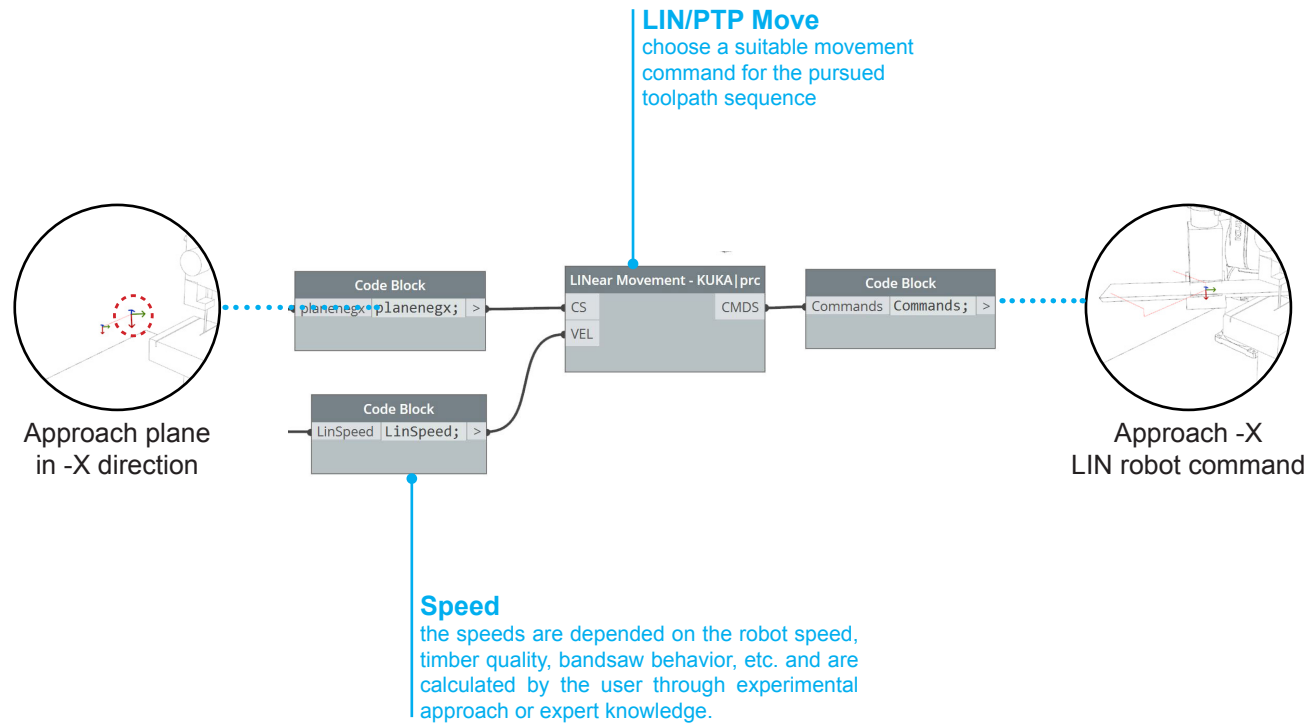
Include the negative component only if movement is planned in negative direction of fabrication plane. If positive, directly plug in Num into A input of Amplify component.



Approach plane in -X direction

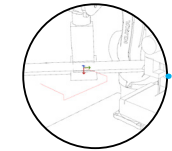
# ROBOT COMMAND FOR APPROACH PLANE IN -X AXIS

Each plane is individually converted to robot commands as the speed for each command is different. The retract and approach can be of similar speed but while cutting the speed needs to be significantly slower to not get stuck or break with the saw band. Again the strategy for developing the algorithm for this step is identical. Develop similar algorithms with different speeds and movement commands based on the approach and retract requirement.

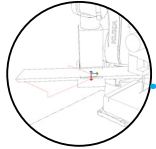




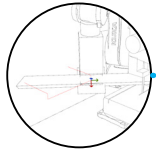
# MERGE ROBOT COMMANDS TO CREATE TOOLPATH



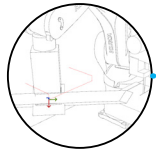
Approach -Y  
PTP robot command



Approach +Z  
LIN robot command



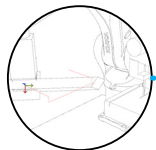
Approach -X  
LIN robot command



Retract +X  
LIN robot command



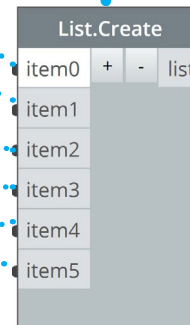
Retract +Z  
LIN robot command



Retract -Y  
LIN robot command

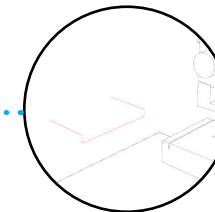
## Command Weave

Combine all robot commands into a sequential toolpath. Make sure the order of the sequence is correct by checking the simulation.

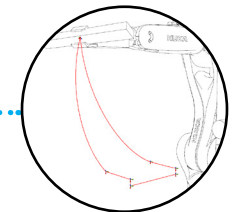


## CoreComponent

PTP start and end movement from and to home position are automatically programmed by the core component.



User defined  
Toolpath

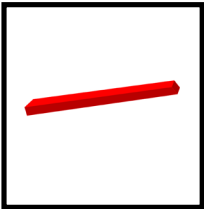


Toolpath

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## EVALUATION

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Challenge: To guarantee seamless robotic execution the designed toolpath needs to be confronted with the constraints of the real world production. To avoid interruptions during real production, the toolpath has to be simulated and checked for manufacturability of the local design unit.

Goal: In this section you learn how to use the simulation and how to user-friendly display manufacturability.

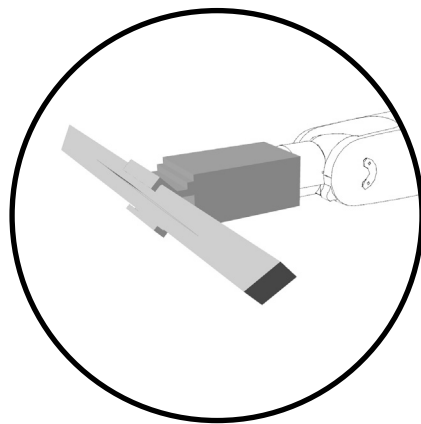
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# DESIGN EVALUATION

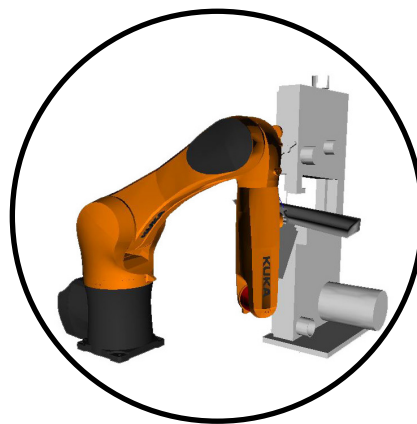
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The design is evaluated every time to identify the non-manufacturable components through another iterative algorithm. The algorithm uses the inverse kinematic solver integrated in the core component, which checks for reachability, collisions, and singularities of the robot simulation. The shown algorithm then highlights the geometries which cannot be manufactured in red while the geometries which can be manufactured are shown in green. This visual illustration informs the designer whether the design can be manufactured or not, throughout the designing process.

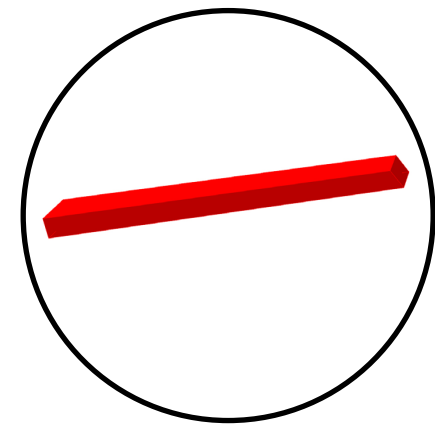
If the evaluation expresses that a local design is not manufacturable, the user has to check the cause of the problem. First of all, the optimization procedures discussed in chapter machine information should be checked. Meaning, is the tool orientation at its best and is front and rear position of cutting chosen wisely. Nevertheless, after all the previously discussed optimization procedures, there are instances where the robot is still not able to manufacture the components (for example when workpiece has exceeded its limits either by length or angle of cut or a combination of both). Then the global design has to be continuously altered by the user through quick modifications of the parametric input until all components are manufacturable.



Generate Robot Tool



Generate Robot  
Simulation



Analyse the  
manufacturability of  
geometry

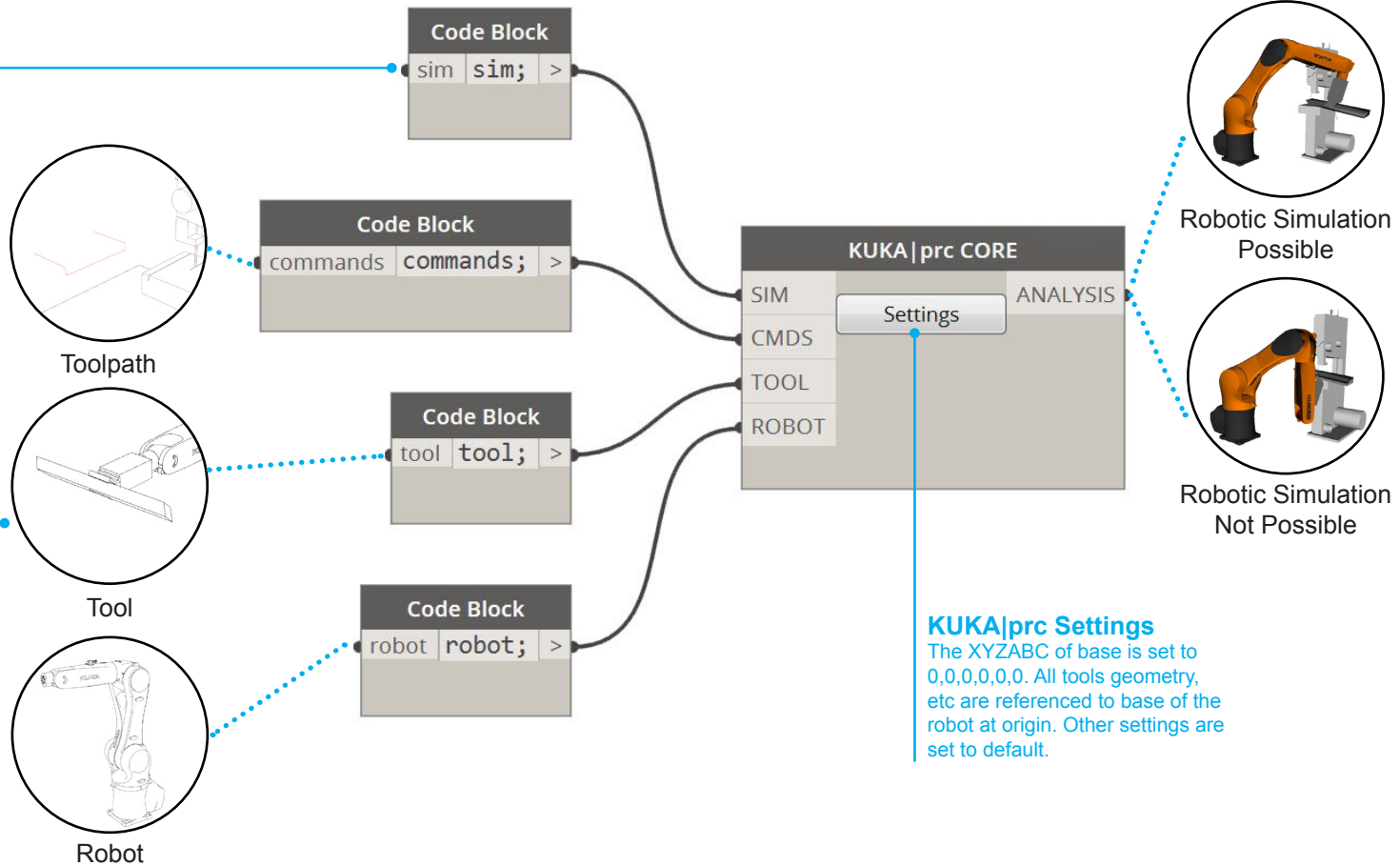
# GENERATE ROBOT SIMULATION

## Number Slider

Animate the slider input to check the simulation

## Tool

Create robot custom tool according to explanation of basic robot programming tutorial (transfer setup data)



## KUKA|prc Settings

The XYZABC of base is set to 0,0,0,0,0,0. All tools geometry, etc are referenced to base of the robot at origin. Other settings are set to default.



## PRODUCTION



After the design is tested and confirmed that all components are manufacturable, the design is sent for production

After production each workpiece is marked with necessary information to be able to manually assemble all pieces at the correct location.

