

WATT 1.5

User's Guide

Heron Technologies bv
P.O.Box 2
7550 AA Hengelo
The Netherlands

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Literature

Erdman, A.G. and Sandor, G.N., 'Mechanism Design: Analysis and Synthesis, Volume 1', (Prentice Hall, 1991, second edition), ISBN 0-13-569872

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Preface

Most software tools available in engineering are aids to help measure, search, collect, register, present and calculate. Finding solutions to a design problem is still dependant on the sum of accessibility and availability of knowledge. The know-how and experience of the engineer involved determines principally the time needed.

In cooperation with the University of Twente (Netherlands), Heron has developed a unique generating technology. Its ability is to offer the engineer suitable solutions based on specifications. The technology makes the knowledge of the expert available for application. A future can be envisioned where the engineer would have a staff of virtual experts at his/her fingertips, getting solutions for each partial problem on command. The responsibility of the engineer will be to judge, decide and configure the total design.

The first product based on this technology **WATT**, “thinks” like an engineer, using linkage and mechanism design theory developed over the past two centuries, combined with search methods and optimization techniques. With a basic knowledge of mechanical engineering and mechanism theory (chapter 5) the software can help you design a variety of complex moving or folding products.

With virtual professors, education of product development engineers can be less domain focused, technically broader and more conceptual. More attention can be paid to physical principles, idea generation, comprehension, problem specification and product configuration.

Generating tools are a bridge to and between theory and practice. They help understand and enable fast application. New theory will be easier and faster available as the real professor updates the virtual one.

We hope you enjoy using WATT,

Heron Technologies bv
Hengelo, The Netherlands
January 2001

1 Introduction

1.1 What is Watt?

Most available software on dynamics or kinematics is used to analyze the behavior of a mechanism. However, to start with, the Engineer has to 'invent' a mechanism before he can analyze it. This is not a trivial task. With available methods and handbooks this can take several days if not weeks.

Watt Mechanism Design Tool solves this problem. From specification of the required movement and constraints on pivot locations, transmission angles, dimensions etc, it searches and finds a variety of approximate or exact solutions within minutes. The Engineer can interactively set specifications, evaluate the offered solutions and add or relax constraints. Instead of painstakingly trying to find one mechanism that might work, the Engineer has a range of solutions out of which one can be chosen. He can focus on integration of the mechanism into the total product.

Watt uses Heron's unique Generating Technology to search for solutions, not using a limited database, but the rules of physics and kinematics.

Designing the user interface puts the Engineer in charge. Watt is easy to use, every command just one click away. No stacking dialogs, no crawling through menus. Watt uses a single window user interface. Important information is always visible. User intervention is always allowed which enables a very interactive working method. Start, stop, change, optimize... etc.

Overview of Specifications	Watt Light	Watt Project	Watt Professional
Animation	✓	✓	✓
Optimization	✓	✓	✓
SI, Metric or US Customary Units (meter, inch, millimeters)	✓	✓	✓
Graphs of path error, velocity, acceleration, transmission angle	✓	✓	✓
Input function definition	✓	✓	✓
4-bar linkage synthesis	✓	✓	✓
4-bar slider synthesis	-	✓	✓
5-bar belt-wheel synthesis	-	✓	✓
Watt 1, 6-bar linkage synthesis	-	✓	✓
Watt 2, 6-bar linkage synthesis	-	✓	✓
Stephenson 1, 6-bar linkage synthesis	-	✓	✓
Stephenson 3, 6-bar linkage synthesis	-	✓	✓
8-bar parallel motion synthesis	-	✓	✓
Path Generation	✓	✓	✓
Motion Generation	✓	✓	✓
Import Path from Excel	✓	✓	✓
Import Output Link from DXF file	-	✓	✓
Import Ground Link from DXF	-	✓	✓
License 1.0 valid	Unlimited	Limited to 3 months (for project use)	Unlimited

1.2 About this User's Guide

This guide contains the following sections:

- Getting started
- Guided Tour
- Reference describing all the features in the program
- Theory section.

If you are new to linkage design it is recommended to start with the theory section, which will help you understand the specific linkage terminology used in this manual and the program.

1.3 What is new in version 1.5

Added functionality

- Joints no longer numbered, but according to mechanism conventions labeled by characters A-Z
- Specific Joints can be forced into a ground pivot or output link area.
- Extra Synthesis Option: "Full Input link Rotation required"
- Export to SAM .dat file
- HTML report contains options dialog, which allows the user to select report filename, parts to print and whether to AUTOPRINT.
- Export to Excel now optionally includes all graphs into the Excel workbook.

Bug fixes

- Calculation error in acceleration data.
- Autostart error through long filenames with spaces.

2 Getting started

2.1 What should be in the package?

This package should contain the following items:

- This manual
- Installation CD-ROM
- Registration info and activation code.

2.2 System requirements

Minimal system requirements

Pentium I 120MHz Computer
32 Megabytes RAM
A hard disk with 20 Megabytes of free space
Microsoft® Windows™ version 95/98/ME/NT/2000

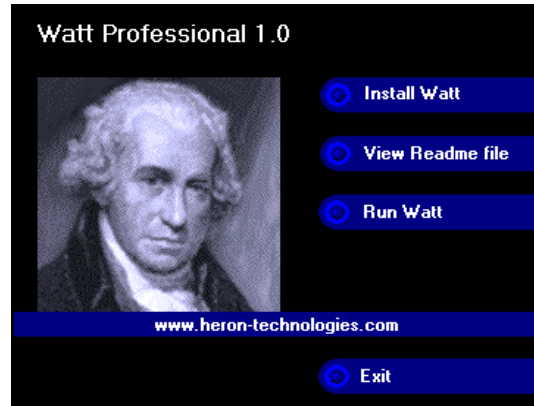
Recommended system

Pentium II 350 MHz. Computer
64 Megabytes RAM
A hard disk with 20 Megabytes of free space

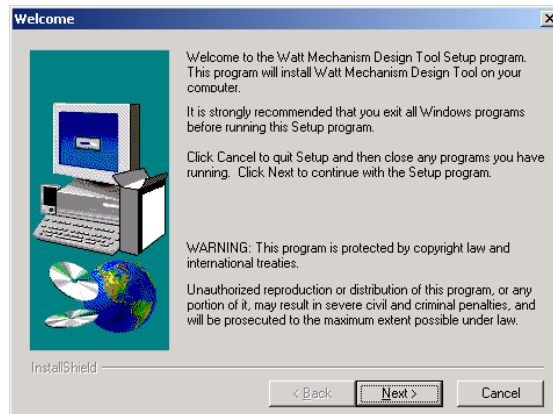
Microsoft® Windows™ version 95/98/ME/NT/2000
Microsoft Excel preinstalled.

2.3 Installation

- Insert the CDROM in its drive and close it. The screen below should appear.
- In some cases this may not happen automatically. Start Windows Explorer, and double-click on the CD icon.

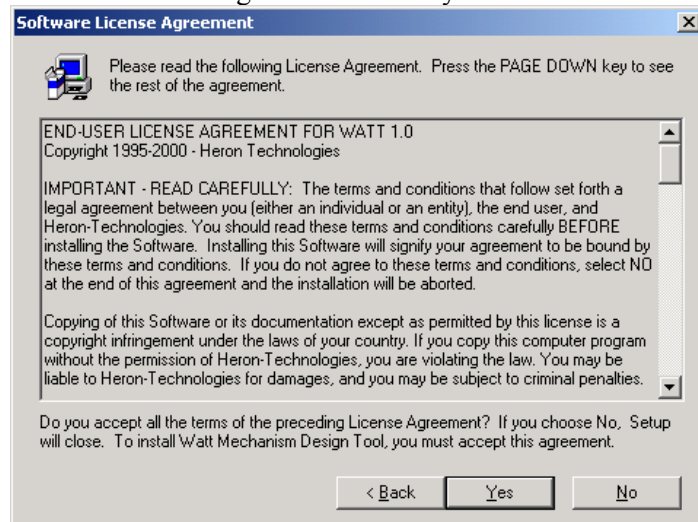


- Click Install Watt

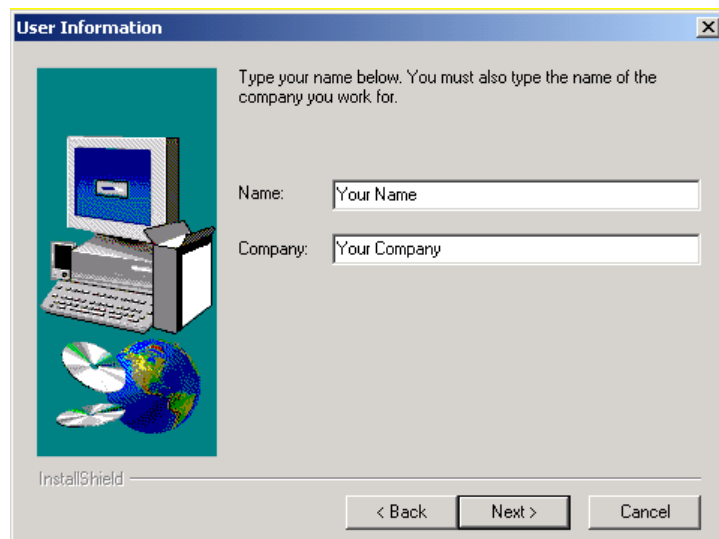


- Click Next,

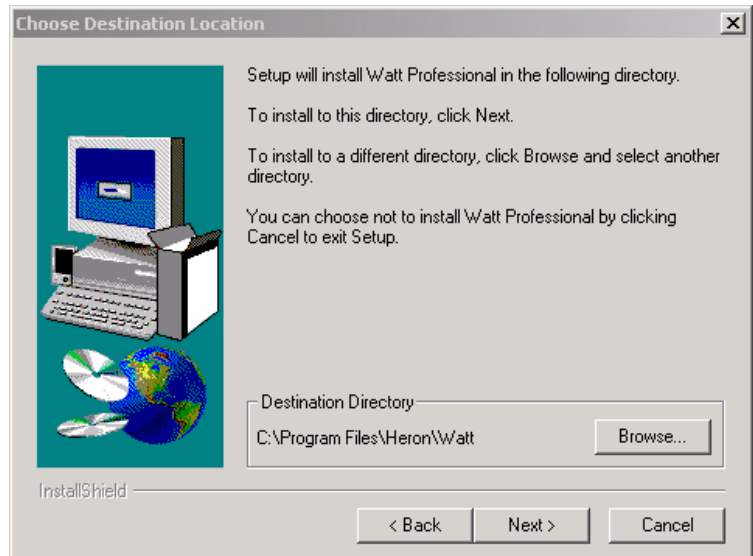
- Read the license agreement carefully.



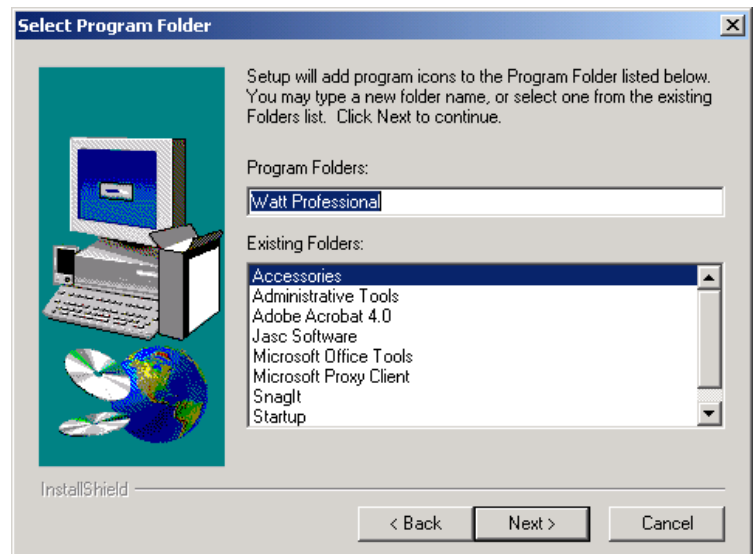
- Select **Yes** if you agree. The installation will continue.



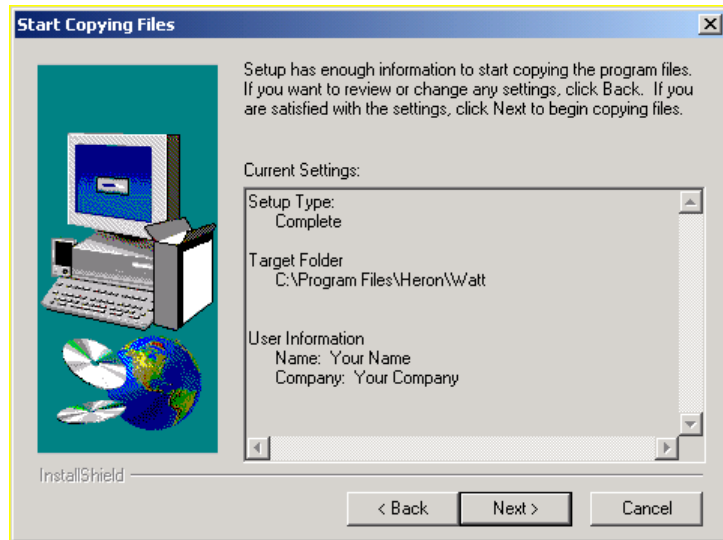
- Type your Name and Company and click Next



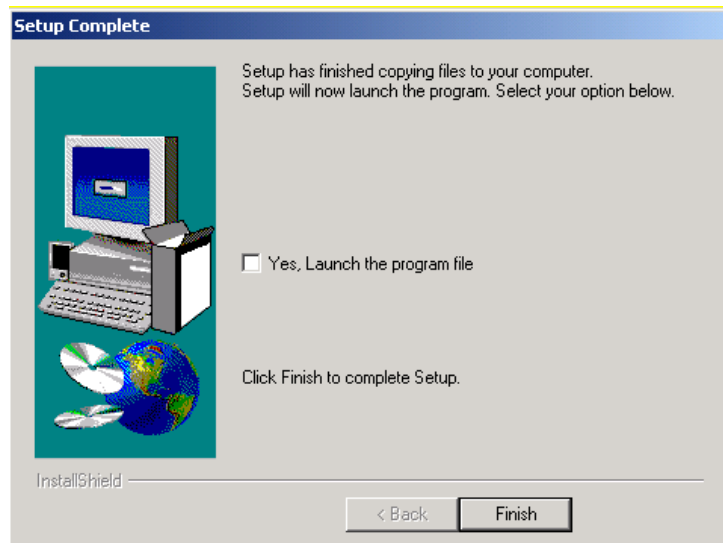
- Click Next (for standard installation).



- Click Next.



- Click Next and the copying of the program files starts.

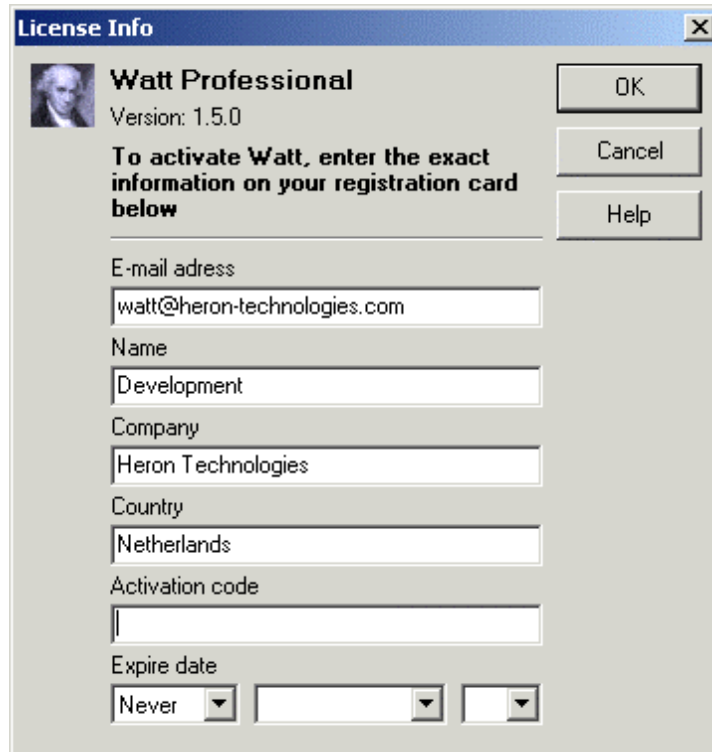
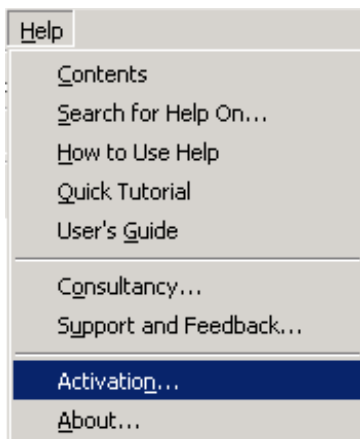


- Select **Yes, launch the program file** to start Watt Professional

2.4 Set license information and activation code

To activate Watt, fill in the license information you have received.

Select **Activation...** from the **Help** menu



3 Guided Tour

3.1 Overview

Start Watt and open the example file: **DXF conveyor example.watt**

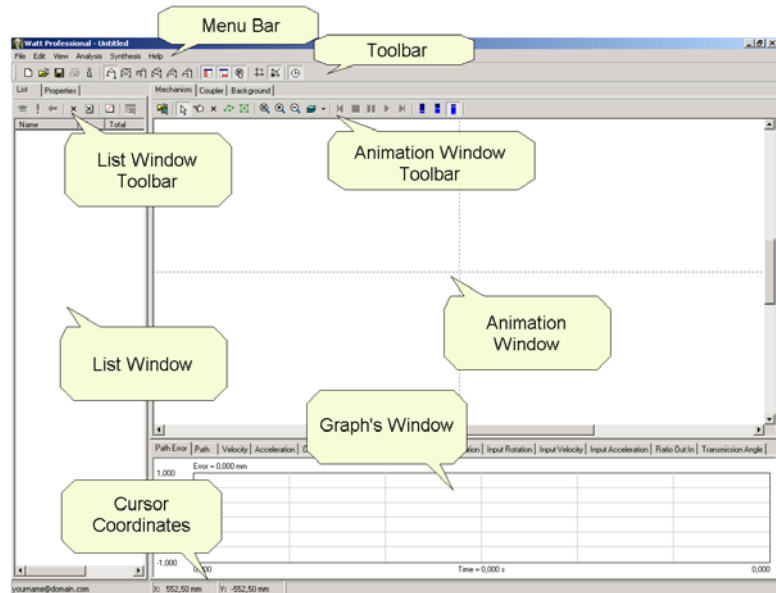
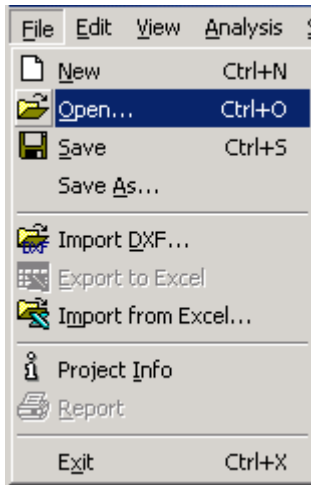
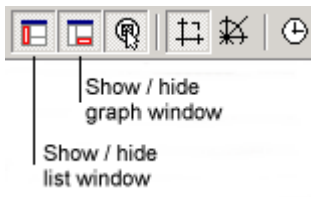


Figure 3-1 Main Window

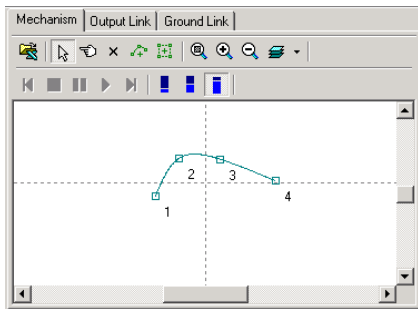
The main window of Watt is roughly divided into three parts. The largest section on the right consists of three tabbed windows, **animation window**, output link and ground link window. To the left is the **list window**, where all generated mechanisms are displayed. At the bottom the **graph window**, showing a graph versus time or input rotation for every selected mechanism.



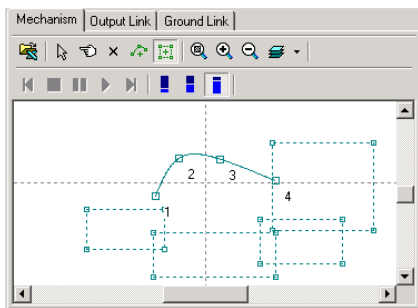
To increase the animation viewing area it is possible to hide the graph and list windows

Animation Window

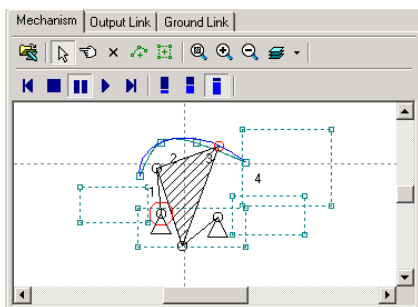
The Animation window will be the main working area.



The first step in searching for a mechanism is defining a required path for the mechanism path point to follow. This will be called the **curve** or **required path**.



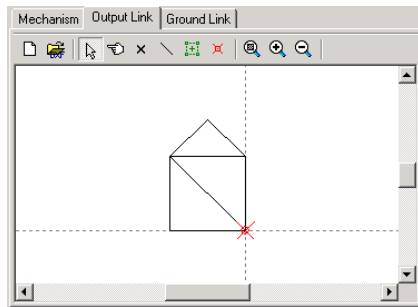
The next step is setting Ground pivot constraints. The ground pivots may need to be fixed in certain areas where there is room to attach bearing constructions.



Once a selection of mechanisms has been generated. Each mechanism in turn can be viewed and animated, by using the VCR style buttons. Using the left and right cursor keys moves the mechanism just one step.

Speed of animation can be set from low to fast.

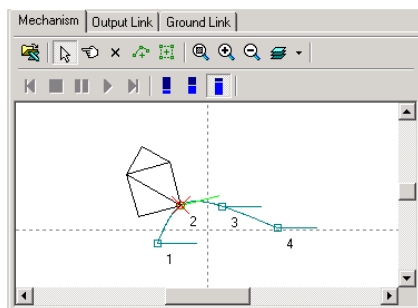
Output Link Window



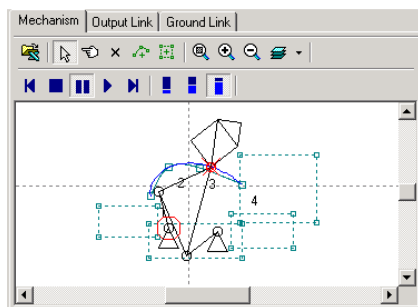
In the Output link window a very simple line drawing can be created. The default drawing is shown to the left. Alternatively any drawing made in the AutoCAD compatible DXF format can be imported and will be displayed instead.

The output link drawing will be connected to the pathpoint of the mechanism at the point marked by the red circle and cross.

This connection point can be dragged to any spot in the Output Link Window



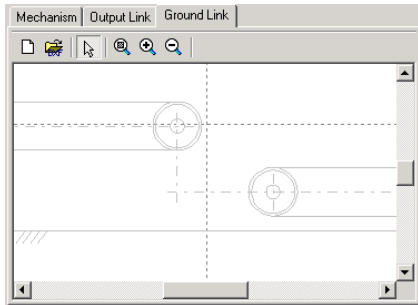
If a curve is defined and an Output Rotation is set, the Output Link drawing will be shown at any **selected** curve point in the position defined by it.



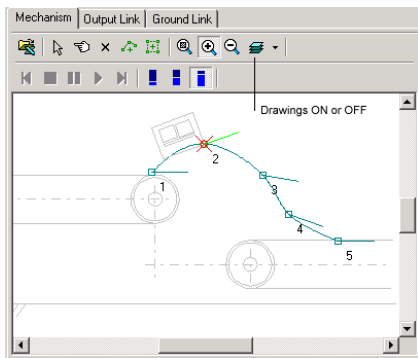
During animation the **output link drawing** will be drawn connected to the output link of the mechanism.

Ground Link Window

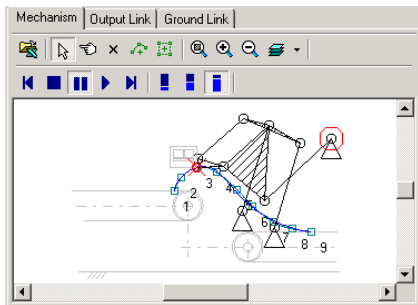
The ground link, foundation or earth can be imported from an AutoCAD compatible DXF drawing.



In the animation window, the drawing can be used as a reference for defining a curve and setting the ground pivot areas.



If switched ON ground link and output link drawing are displayed during animation.



List Window

Name	Nr	Total
Eight Bar	35	0,0041196
Watt 2	16	0,0051740
Watt 1	9	0,0080540
Watt 1	11	0,0086255
Stephenson 1	27	0,0086854
Watt 2	18	0,0103059
Eight Bar	40	0,0104359
Fourbar	1	0,0116436
Watt 2	19	0,0120826
Slider Four Bar	5	0,0124844
Eight Bar	33	0,0129322
Stephenson 1	30	0,0134587
Stephenson 3	26	0,0143859

At the top of the list window are the buttons to start generating, optimize, undo optimization, delete, clear list, input function definition and export to Excel.

The list itself displays linkages in order of suitability. This means the mechanism is situated higher in the list, the better the path fits the defined curve and the more the rotations of input and output link fit the requirements. The number in the **Total** column contains a combined error value. A low value means best fit.

In the **Nr** column each mechanism has a unique number to identify it.

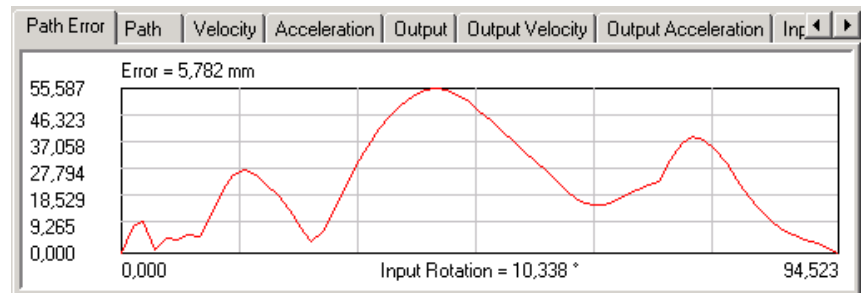
Click a mechanism in the list to select and view it.

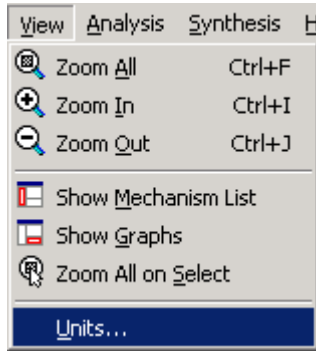
Double click to start animation.

Graph Window



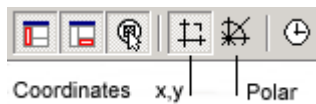
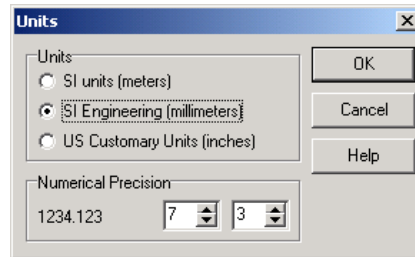
The graph window displays properties of the selected mechanism versus time or input link rotation.



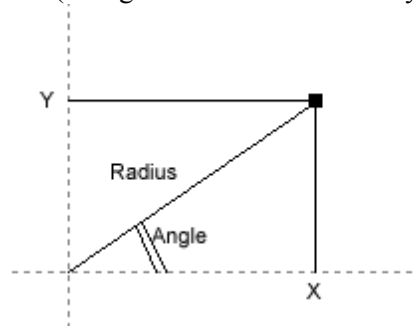


3.2 Setting preferred units and coordinates

Depending on the part of the world you are in, you might want to use SI units, US Customary units or Engineering metric. Select **Units...** from the **View menu** to set your preference. At any time you can change the settings to view the results in another unit system.



Watt can work in the Cartesian (x,y) or the Polar **coordinate system**. Set to your preference (changes are reflected instantly)

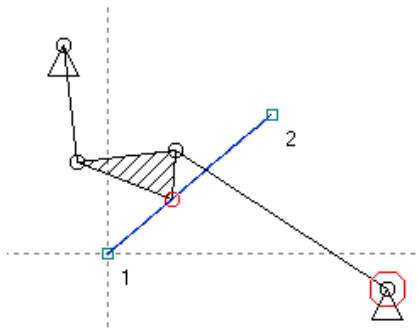


Important note: Throughout the program and for all export and import functions Watt uses the **unit** and **coordinate system** settings.

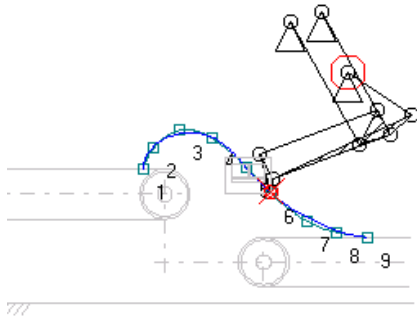
3.3 How to setup a problem?

Watt solves two commonly encountered problems in mechanism design:

1. Path Generation
2. Motion Generation



Path Generation is the task to create a mechanism of which a point will describe a certain trajectory. Rotations of the output link do not matter. E.g. a straight line mechanism. In most cases these mechanisms will be part of a larger machine.



Motion generation is the task to move an object along a trajectory. Rotations of the object (connected to the output link) are essential. An example is the **DXF conveyor example.watt**, where a box has to be moved from one conveyor belt to another while staying in the same upright position.

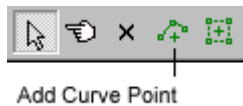
Before setting a problem for **Watt** to solve, it is essential to isolate the mechanism problem from your total design problem of the machinery or product you are working on. Find out if it is a path problem or a motion problem.

It is always advisable to look for more than one way to define the problem for Watt and play around with some alternative settings.

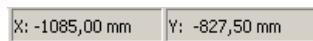
Use of a DXF background as reference or a pre calculated path imported from Excel, will ease the effort of trying alternatives.

Defining a required path

The first step is to create a curve the mechanism path-point should follow. Create a curve by defining individual points. The points will automatically be connected by a spline.



1. Click the **add curve point** button in the Animation Window Toolbar.
2. Move the cursor to a suitable spot in the window and left click.



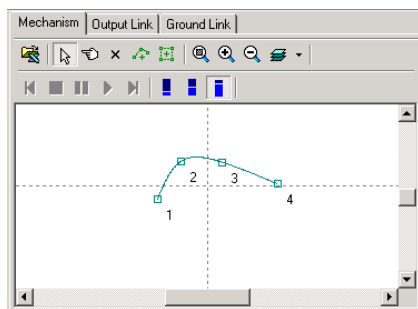
Cursor coordinates are displayed at the bottom of the graph window.

Move a curve point:

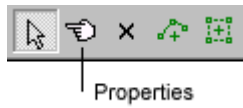


1. Click on the Select button to set **selection mode**,
2. Left click on a curve point and hold down the mouse button while dragging it to the required spot.

Setting two points will create a straight line. Adding curve points will automatically create a smooth curve.



Use as many points as needed.



Set the coordinates:

1. Click the Properties button.
2. Click on a curve point.
3. The Curve Point dialog appears.
4. Set the required coordinates

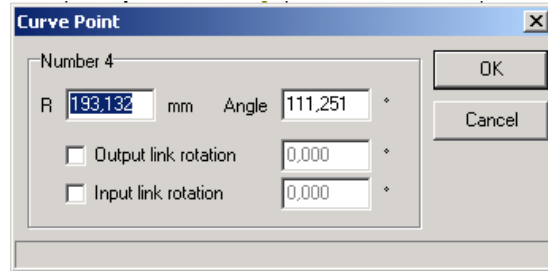


Figure 3-2 Edit Curve Point



Alternative

1. Click the Select button
2. Double click a curve point
3. The Curve Point dialog appears
4. Set the required coordinates

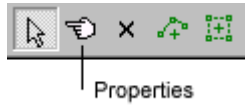


Delete a curve point:

1. Click the Delete Button
2. Move the cursor to the point to be deleted.
3. Click

Rotation

For motion generation problems a required rotation angle of the output or input link can be defined.



1. Click the Properties Button
2. Click on a curve point.
3. Select the Output Link Rotation and/or Input Link Rotation field
4. Define the angle of rotation required at the selected point.

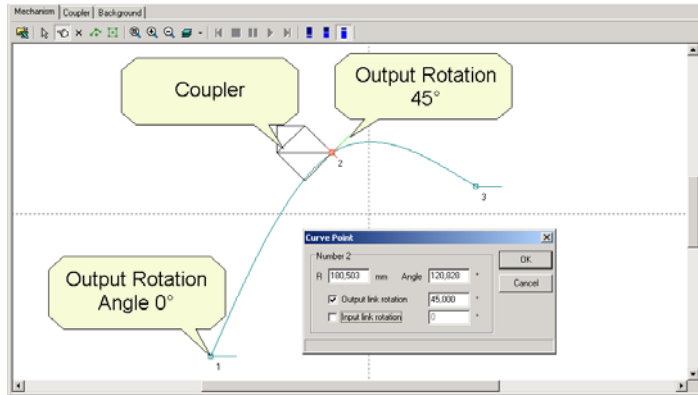
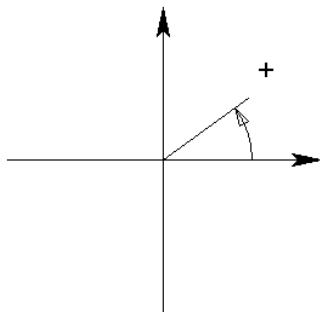


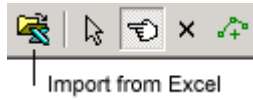
Figure 3-3 Edit Rotation



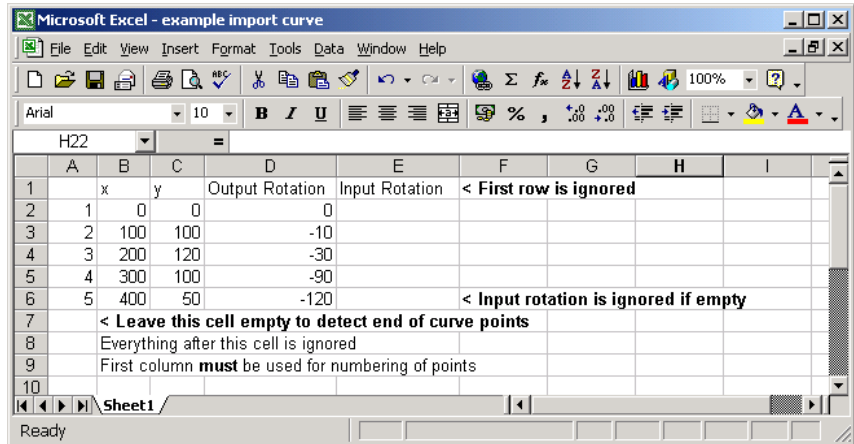
Important note: Rotation is relative to the starting position. Therefore the rotations of curve point 1 cannot be changed from its default 0 degree value.

Positive angles result from anti-clockwise rotation from the positive x-axes.

Import from Excel



It is also possible to define the curve points in an Excel-sheet. The Excel file must be formatted as shown in the file: *example import curve.xls*. The comments in the file give more information.



Important note: the unit and coordinate settings are used to import and convert the curve point values.

3.4 Define Ground link pivot areas

Add area

The position of the ground pivots may need to be constrained to places where they can be attached to a structure. If this is the case ground pivot areas need to be defined. Ground pivots are only allowed within these areas.



Define an area:

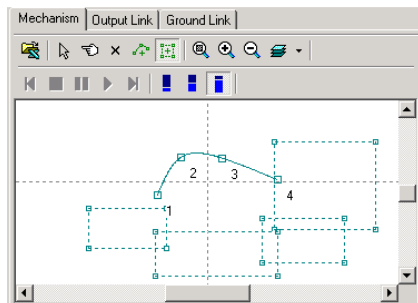
1. Click the **add area** button.
2. Click and drag anywhere on the view window.
3. Add areas to cover all available space. Areas can overlap.

Resize an area:

1. Click the select button
2. Click and drag one of its corners or edges

or

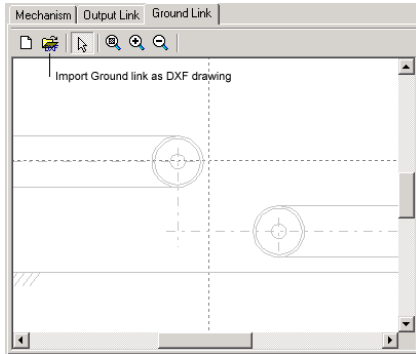
1. Click the Properties button
2. Click on one of its corners or edges.



It is much more intuitive to set the areas in respect to an existing drawing. To do this import a DXF –file in the Ground Link window.

In Watt version 1.5 it is possible to force specific joints into an area.

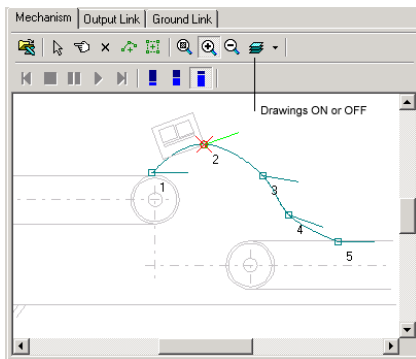
Import DXF ground link



To facilitate path definition and selection of ground pivot areas, an existing DXF drawing can be imported as ground link.

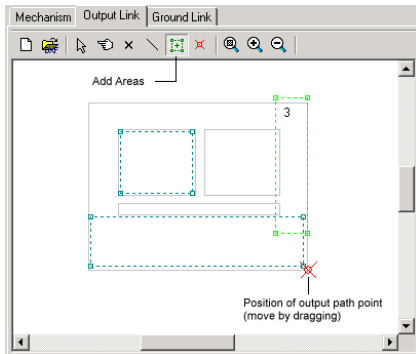
1. Select the ground link window.
2. Click on the import DXF-icon
3. Select a DXF-file to import

In the animation window, the drawings of output or ground link can be switched ON or OFF.



3.5 Define Output link pivot areas.

Add Area

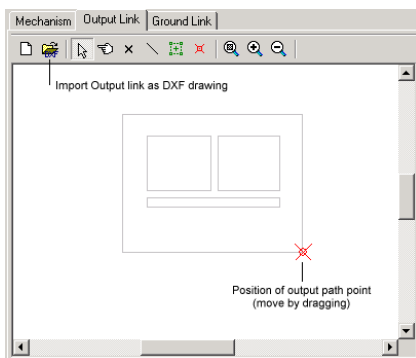


The position of the output link pivots may need to be constrained to places where they can be attached to the object. If this is the case, output link pivot areas need to be defined. Output link pivots are only allowed within these areas.

1. Select the **output link** window.
2. Click the **add area** button
3. Add areas where pivots are allowed.

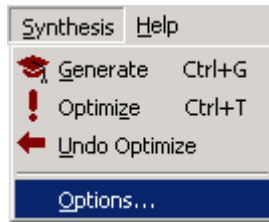
Import DXF output link.

Import DXF



Instead of using the default output link drawing, one can be imported from a DXF-file.

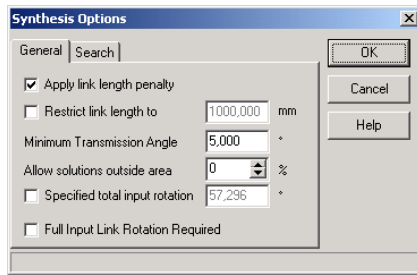
1. Select the **output link** window
2. Click on the **import DXF**-button
3. Select the DXF-file



3.6 Synthesis options.

Select Options from the synthesis menu to set synthesis options.

General



Link length penalty on: If checked it prevents generation of linkages with very long link length, by adding a penalty during the search process.

Restrict Link Length to: In certain applications it may be advisable to restrict link lengths to a maximum value.

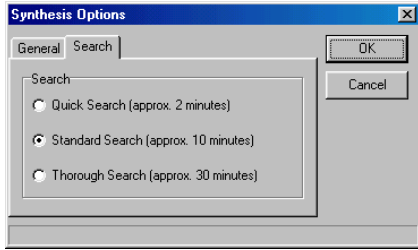
Minimum transmission angle: small values of the transmission angle can lead to blocking of the mechanism. Restrict to at least 5 degrees.

Allow solutions outside area: If no solutions present itself, this may be caused by too restrictively set Ground Pivot Areas or Output Link Areas. Without changing the actual areas, the search areas can be increased by a percentage of surface area to find out if any solutions are available outside the current settings.

Specified total input rotation: if the application requires a specific rotation of the input angle and all rotations in between do not matter, select this option instead of setting the input rotation in the Curve Point Settings.

Full Input Link Rotation required: Check this option if you require a mechanism of which the input link must be able to rotate full 360° without blocking. (Version 1.5)

Search Depth



Thorough Search is recommended for finding the best solutions. On 1GHz and faster processors this is achieved in acceptable time.

Set standard search for Pentium II and Pentium III computers

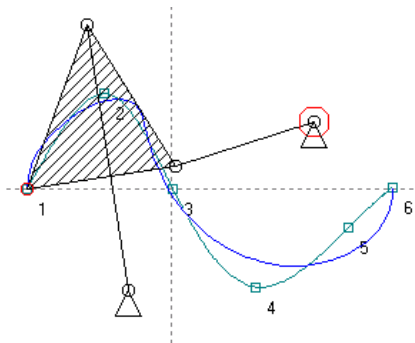
Quick Search is only for quick exploration or very slow processors.

3.7 Select a mechanism type



Select a mechanism appropriate to the problem stated. It is always a good idea to start with a four bar is

1. Four bar
2. Four bar slider
3. Five bar belt-wheel
4. Watt 1, six bar
5. Watt 2, six bar
6. Stephenson 1, six bar
7. Stephenson 3, six bar
8. Eight bar, parallel motion



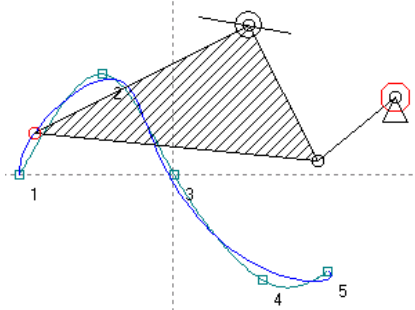
Four bar

When to use:

A fourbar mechanism is the most versatile and simple linkage.

Problems:

Setting a path, output rotation and input rotation at the same time does rarely result in any solutions. Parallel motion is impossible.



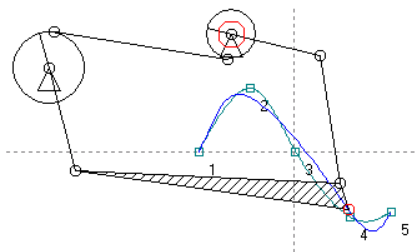
Four bar slider

When to use:

Like a fourbar this mechanism is a very versatile and simple.

Problems:

Setting a path, output rotation and input rotation at the same time does rarely result in any solutions. Parallel motion is impossible.

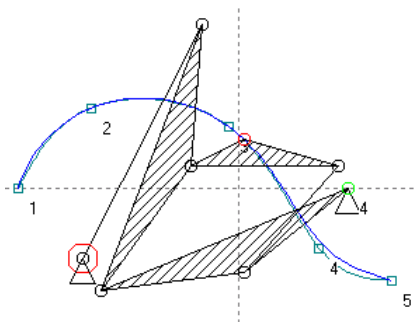


Five Bar

A five bar with a wheel and belt connection between both grounded links.

When to use:

Best suited if the Output Link rotation is set.

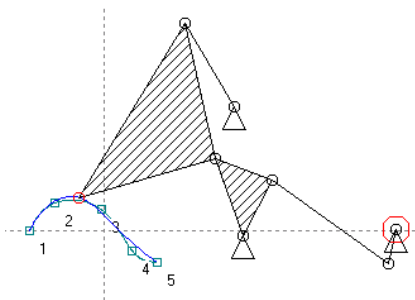


Watt 1, six bar

Watt 1 is a four bar mechanism with a function generator between one grounded link and the output link.

When to use:

Best suited if the Output Link rotation is set. If output rotation is free, **parallel motion** is assumed.



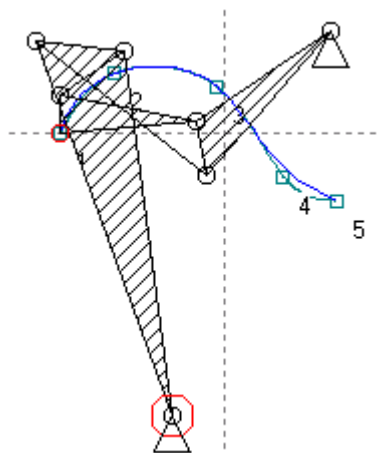
Watt 2 six bar

When to use:

Best suited if the Input Link rotation is set. If no input rotation is set, the mechanism will be generated in such a way that a 360 degree rotation of the input link moves the path point up and down the path. The input joint can be moved without affecting the path.

Problems:

Hardly any solutions, when ground pivot areas are set.



Stephenson 1, six bar

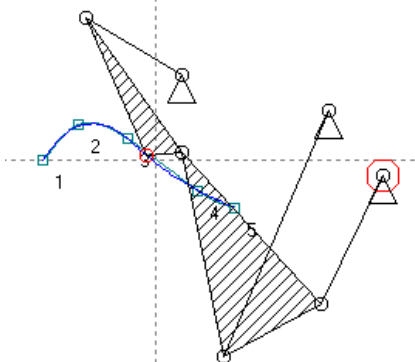
The Stephenson 1 six bar mechanism can be seen as a Five Bar with a function generator mechanism between both ground links.

When to use:

Well suited if Output Link rotation is set.

Problems:

Restricted range of motion due to function generator



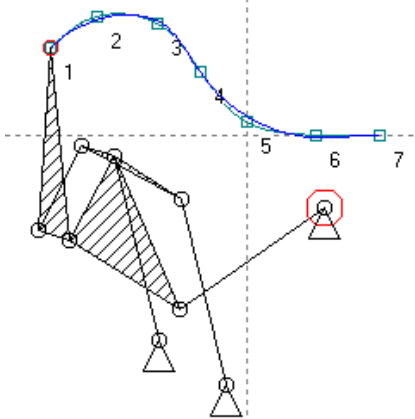
Stephenson 3, six bar

When to use:

When Output Link Areas or output link rotations are set.

Problems:

Multiple rotations of output link and bad transmission angles.



Eight bar parallel motion

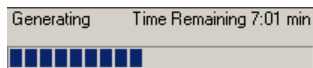
When to use:

The eight bar mechanism generated by Watt is set to provide only **parallel motion**. All pivots except the output point can be moved without affecting the resulting path.

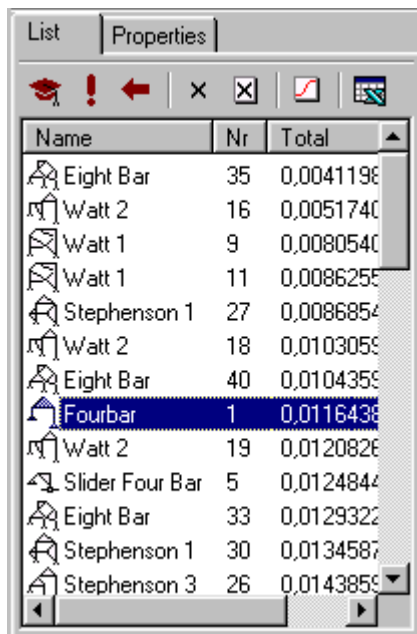
3.8 Synthesis, generating.



The minimum data needed to start generating mechanisms is a required path. If this path is defined, click the Generate button to start the search for suitable mechanisms.



At the bottom of the List Window a progress bar gives an indication of the time left to complete the search.



Solutions will appear in the list window. Each solution gets a sequence number. The mechanism at the top of the list best fits the desired qualifications.

At any time click in the list to view the mechanism, without stopping the search process.

Double clicking will stop the search process and start animating the selected mechanism.

Click the Generate button to **resume** the search.

Note: if no (suitable) solutions appear, it may be the selected mechanism is unable to comply with all restriction. Try other mechanism types, rethink your constraints and set **Synthesis Search Options** to **Thorough Search**.

A fourbar is limited by its configuration in what it can do. Most linkages generate paths that can be seen as part of a distorted figure 8.

3.9 Evaluate results

Animation



A visual scan and animation of mechanisms from the list is the next best step after completing the search process. Use the buttons in the animation toolbar.

1. Step Back (Left Arrow),
2. Stop
3. Pause (Space bar)
4. Start (Space bar)
5. Step Forward (Right Arrow)
6. Low animation speed
7. Medium animation speed
8. High animation speed

Mark a mechanism for future reference by right clicking on the mechanism in the list window and selecting **Mark**. The mechanism icon will turn green.

Note: the animation speed does only affect the speed of animation and **not** the velocity and or accelerations of the mechanism.

Graph

Apart from the path error and transmission angle, the graph window displays velocity and accelerations of input link, output link and the path point. These values depend on the selected input function and the timing set.

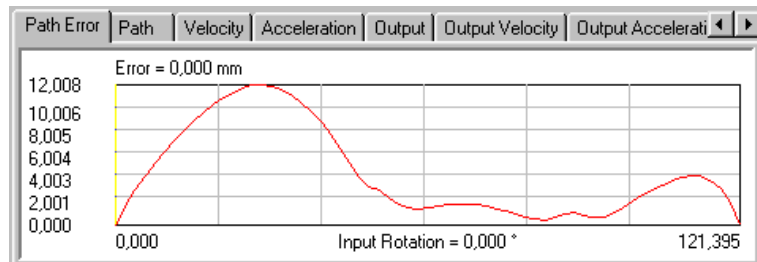
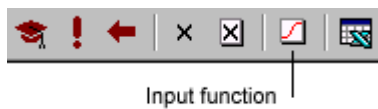


Figure 3-4 Graph Window



To adjust the input function click the input function button at the top of the list window.

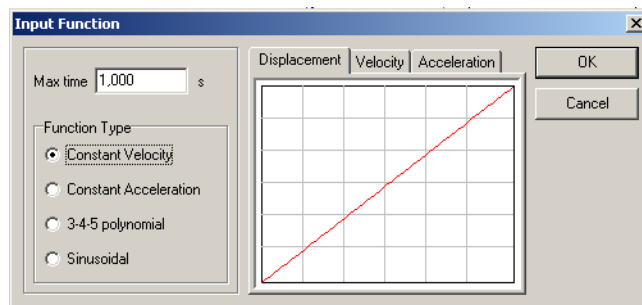


Figure 3-5 Input Function Window

Max Time: time to complete movement along the path from start to finish.

Function Type:

1. Constant velocity = e.g. electromotor running at constant speed
2. Constant acceleration = e.g. spring, pneumatic or hydraulic actuator.
3. 3-4-5 polynomial = cam or servo
4. Sinusoidal = cam or servo

Velocity and acceleration profiles are visible for each function.

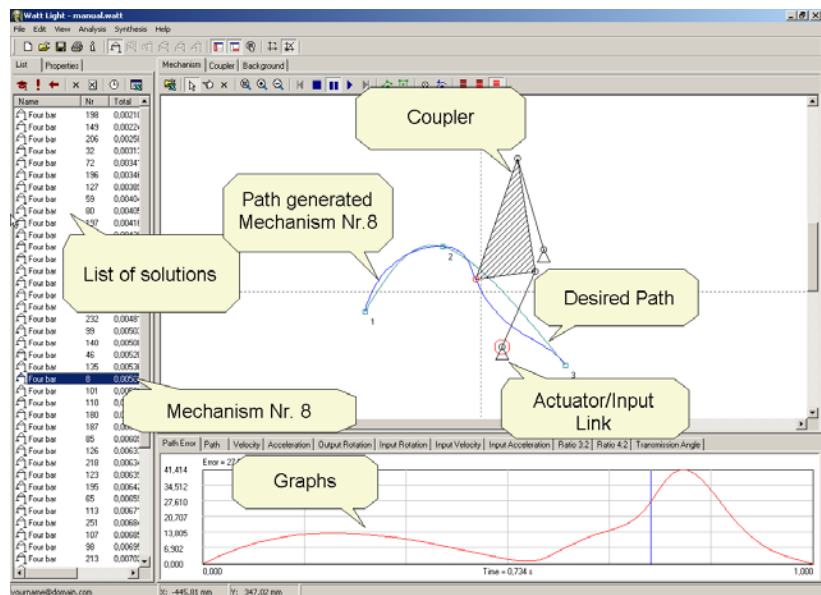
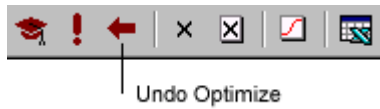
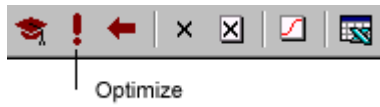


Figure 3-6 Generated Solutions

3.10 Optimize



A selected mechanism can be optimized, to make it fit the requirements even better.

- To start, click the Optimize button.
- At completion the icon of the mechanism turns red.
- An optimized mechanism will move higher up the list.

If the optimized mechanism is less suitable, the effect of Optimization can be undone.

Figure 3-6 and Figure 3-7 show how path error has significantly decreased after optimization.

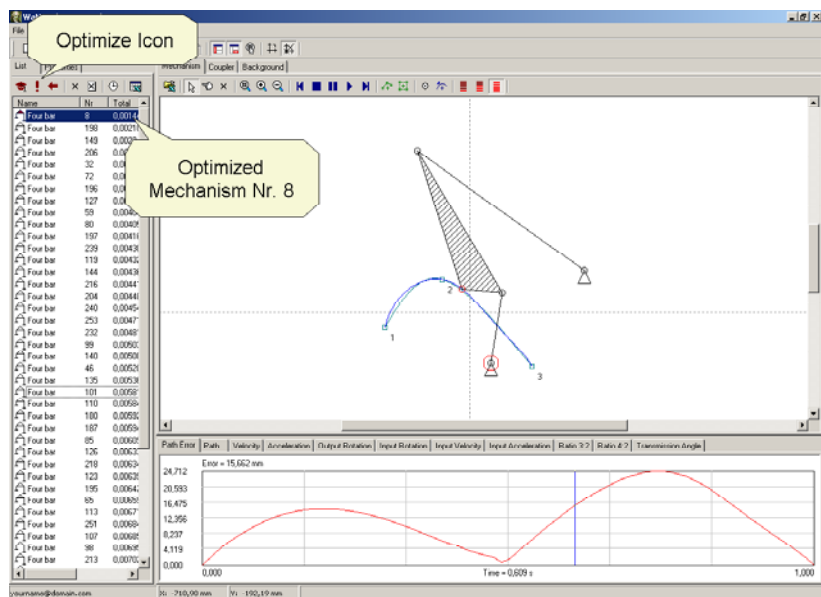


Figure 3-7 After Optimization

3.11 Export to Excel.



This option generates a Microsoft Excel workbook or folder (depending on the Excel version installed on your computer). It contains several sheets.

1. Mechanism dimensions
2. Data related to the motion of the mechanism
3. Graphs related to motion data

Data can be used:

- As input for CAD programs.
- Further processing or calculation

Note: **unit** and **coordinate system** settings affect the output and number formatting.

3.12 HTML Report



All properties of the selected mechanism are saved to a HTML file and shown in your default browser (Netscape or Explorer). This file is saved in the same directory as the current project. A HTML file can be edited by Word, Frontpage, StarOffice etc.

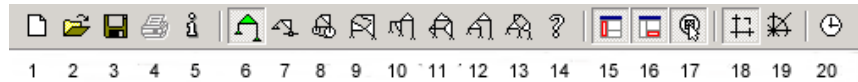
The graph data displayed depends on the selected graph tab. No graph data is displayed when the graph window is hidden.

Velocity and acceleration values are dependent on the input function settings.

Note: **unit** and **coordinate system** settings affect the output and number formatting.

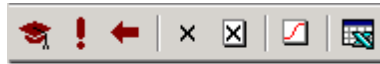
4 Guide to tools, menus graph's etc.

4.1 Main Toolbar



1. New project
2. Open existing project
3. Save
4. HTML Report
5. Project Info
6. Four bar
7. Slider four bar
8. Five bar
9. Watt 1, six bar
10. Watt 2, six bar
11. Stephenson 1, six bar
12. Stephenson 3, six bar
13. Eight bar, parallel motion
14. Information on mechanism types
15. Show/Hide List Window
16. Show/Hide Graph Window
17. Zoom All On Select
18. Carthesian or x,y coordinates
19. Polar coordinates
20. Graph versus time or input angle

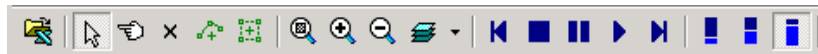
4.2 List Window Toolbar



1 2 3 4 5 6 7

1. Start Generating Mechanisms
2. Optimize Selected Mechanism
3. Undo Optimization of selected Mechanism
4. Delete Selected Mechanism
5. Clear List
6. Input Function settings
7. Export Selected Mechanism to Excel

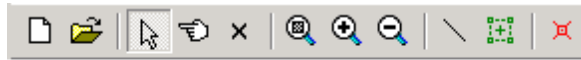
4.3 Animation Window Toolbar



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

1. Import a Mechanism from Excel
2. Select
3. Display property dialog of object
4. Delete
5. Add curve point
6. Add Area
7. Zoom All
8. Zoom In
9. Zoom Out
10. Show/Hide output link drawing, ground link drawing or instant centers
11. Step Back (Left Key)
12. Stop animation
13. Pause animation (Space bar)
14. Start animation (Space bar)
15. Step Forward (Right Key)
16. Low Animation Speed
17. Medium Animation Speed
18. High Animation Speed

4.4 Output Link Window Toolbar



1 2 3 4 5 6 7 8 9 10 11

1. Create new output link drawing
2. Import DXF drawing
3. Select
4. Display Properties
5. Delete
6. Zoom All
7. Zoom In
8. Zoom Out
9. Draw lines
10. Add output link pivot area
11. Set path point connection coordinates

4.5 Ground Link Window Toolbar

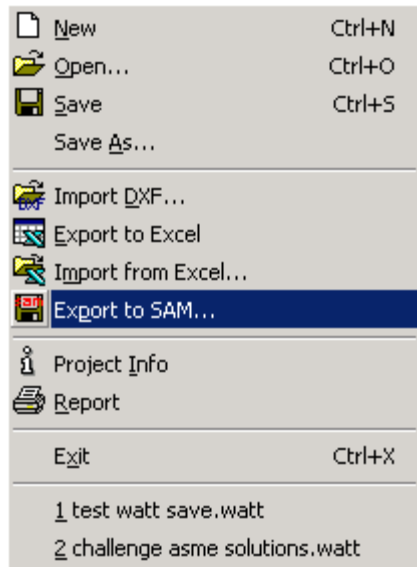


1 2 3 4 5 6

1. New
2. Import DXF
3. Select
4. Zoom All
5. Zoom In
6. Zoom Out

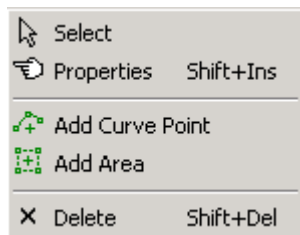
4.6 Menus

File menu



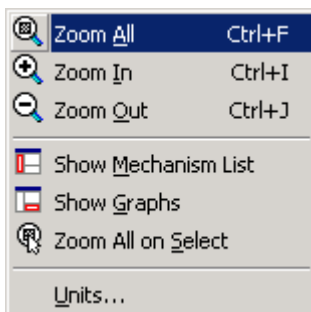
New	Start new project
Open	Open existing project
Save	Save project
Save As	Save project using a new name
Import DXF	Import DXF-file as ground link
Export to Excel	Export properties of the selected mechanism to a MS-Excel file.
Import from Excel	Import curve points from an Excel file
Export to SAM...	Export to SAM compatible .dat file
Project Info	Additional project related information
Report	Create HTML report and show in browser
Exit	Exit Watt
1	Open last saved project

Edit menu



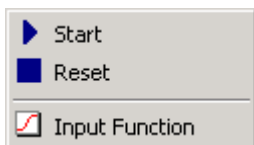
Select	Select Element
Properties	Show properties
Add Curve Point	Add curve point in the animation window
Add Area	Add area where pivots are allowed
Delete	Delete an object

N.B.: right click in animation window to pop up this menu.



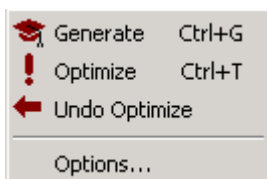
View menu

Zoom All	Zoom to fit all inside window.
Zoom In	Select desired zoom area
Zoom Out	Click in window to zoom out.
Show Mechanism list	Show/Hide list window
Show Graphs	Show /Hide Graph window
Zoom All on Select	Zoom All when selecting a mechanism from the list
Units...	Set preferred units and numerical precision



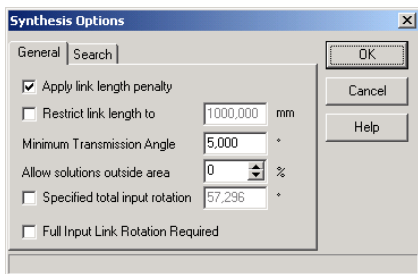
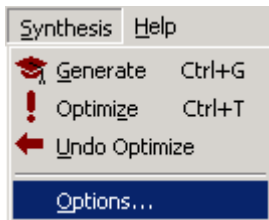
Analysis menu

Start	Start animation
Reset	Reset mechanism to starting point
Input function	Define timing and input function type



Synthesis menu

Generate	Start generating mechanisms
Optimize	Optimize selected mechanism
Undo Optimize	Undo optimization, mechanism is reset to former dimensions



Synthesis options.

General

Link length penalty on: If checked it prevents generation of linkages with very long link length, by adding a penalty during the search process.

Restrict Link Length to: In certain applications it may be advisable to restrict link lengths to a maximum value.

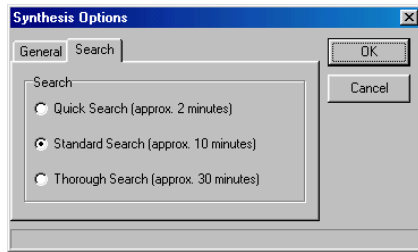
Minimum transmission angle: small values of the transmission angle can lead to blocking of the mechanism. Restrict to at least 5 degrees.

Allow solutions outside area: If no solutions present itself, this may be caused by too restrictively set Ground Pivot Areas or Output Link Areas. Without changing the actual areas, the search areas can be increased by a percentage of surface area to find out if any solutions are available outside the current settings.

Specified total input rotation: if the application requires a specific rotation of the input angle and all rotations in between do not matter, select this option instead of setting the input rotation in the Curve Point Settings.

Full Input Link Rotation required: Check this option if you require a mechanism of which the input link must be able to rotate full 360° without blocking. (Version 1.5)

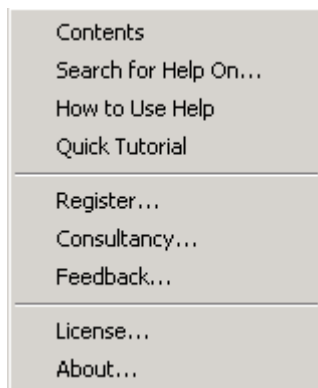
Search Depth



Thorough Search is recommended for finding the best solutions. On 1GHz and faster processors this is achieved in acceptable time.

Set standard search for Pentium II computers

Quick Search is only for quick exploration or very slow processors.



Help menu

- | | |
|--------------------|--|
| Contents | Show contents of Help |
| Search for Help on | Search Help file by key word. |
| How to use Help | General help on Windows. |
| Quick Tutorial | A quick introduction how to use WATT. |
| Consultancy | www.heron-technologies.com/consultancy . |
| Feedback | E-mail to Heron-technologies |
| License | License Information and activation code |
| About | Version, Credits etc. |

Graph Window

Path error	Deviation of path from the curve. Deviation is measured as distance between a path point and a point on the curve with the same relative path position.
Path	Displacement of output point along the path.
Velocity	Velocity of path point
Acceleration	Acceleration of path point (Vector sum of tangential and normal acceleration)
Output	Output link rotation
Output Velocity	Output link rotational velocity
Output Acceleration	Output link rotational acceleration
Input	Input link rotation
Input Velocity	Input link rotational velocity
Input Acceleration	Input link rotational acceleration
Ratio Out:In	Momentary ratio Output link rotation : Input link rotation
Transmission angle	Minimum transmission angle in mechanism

Note: velocity and acceleration depends on the input function settings.

5 Theory on linkage design

5.1 Theory

A mechanism is a mechanical arrangement meant to conduct motion and forces from an input to an output, the magnitude of the motion and forces changes. In the field of kinematics a mechanism consists of rigid links interconnected by e.g. pivots, in such a way that one or more loops or chains are formed. One link of the kinematic chain, is considered to be part of the 'stationary' world. This earthed link is being referred to as earth or ground link. A mechanism allows relative motion between the links.

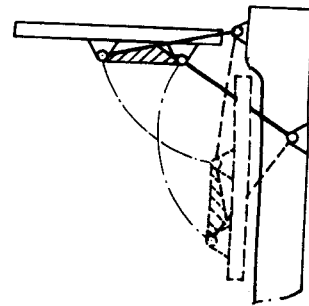


Figure 5-1 Folding Table

Mechanisms can be found in all sorts of appliances that surround us in everyday life: doors of trains, umbrellas, car engines, door locks etc. Mechanisms consisting of links with pivoting, rolling or sliding joints perform a guiding function. The actuation of a mechanism can be achieved by applying a rotating (e.g. electric motor) or by a translating actuator (e.g. pneumatic or hydraulic cylinder, linear motor or spring). Mechanisms with elastic hinges are applied as guidance in precision instruments.

Planar mechanisms

Most applications of mechanisms provide guidance in one plane (x,y-plane) These mechanisms are called planar mechanisms. A planar mechanism guides a body in three coordinates: translation in the x- and the y-direction and rotation around the z-axis. Bear in mind that a planar mechanism should be implemented in a 3D world. Simply setting two of the same mechanisms side by side is not a very good solution. Consider the mechanism for opening the door of a train or bus. The motion of the door is being described by a four bar mechanism in the x-y plane. Unwanted motion in the z-direction or rotation around x,y axes is constrained by a single link connected to a (torsional stiff) steel tube lower at the door.

The four bar

A very simple mechanism in the form of a closed loop is a four bar. The mechanism consists of three moving links, and a stationary ground link. All links are connected by pivots (Figure 5-2).

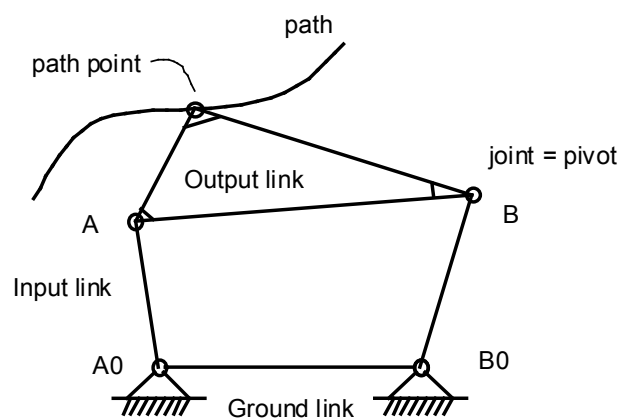


Figure 5-2 Four Bar

The joints are indicated with a letter. Ground link joints get an index 0 . The link connected to the actuator (A_0A) is called the input link. The link connecting joints A and B is called the coupler or floating link in this case it is also the output link. Figure 5-3, Figure 5-4 and Figure 5-5 show three functions that can be performed by mechanisms.

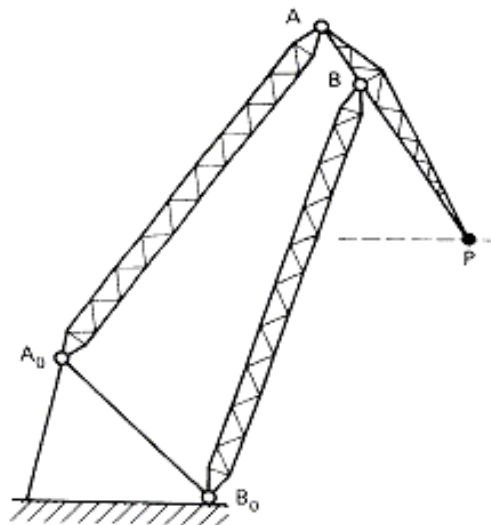


Figure 5-3 Path Generator as Crane

The crane in Figure 5-3 is a special type of four bar. Point P on the coupler describes within certain limits a straight line. A load can be moved in such a way, the potential energy doesn't change. Cranes of this type can be found in docks. This mechanism describes a predetermined path and is referred to as a **path generator**.

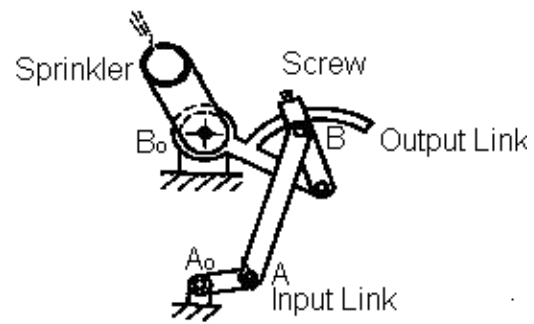


Figure 5-4 Function Generator as Sprinkler

The sprinkler in Figure 5-4 (output link) makes rocking motion as the input link makes a full rotation. Adjusting the length of the output link changes the stroke.

This mechanism creates a desired relation between input link and output link **rotation**. The output link is not a floating link but a grounded link. The mechanism is called a **function generator**.

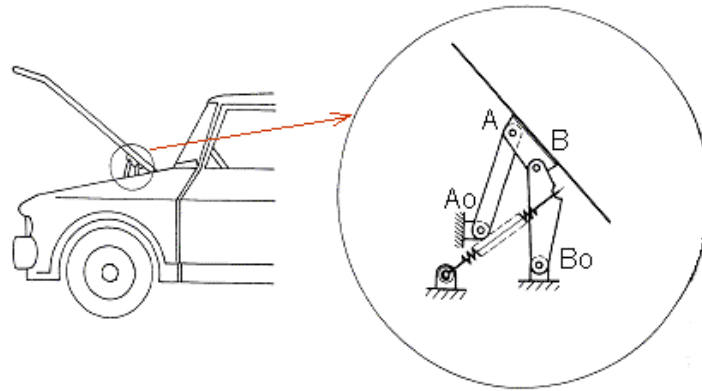


Figure 5-5 Motion Generator as Car Hood

Figure 5-5 shows a four bar mechanism that provides a desired translation as well as a desired rotation of the car hood. The output link guides the hood in such a way it opens fully and closes properly even though its side near the window is curved.

The mechanism type is called a **motion generator**.

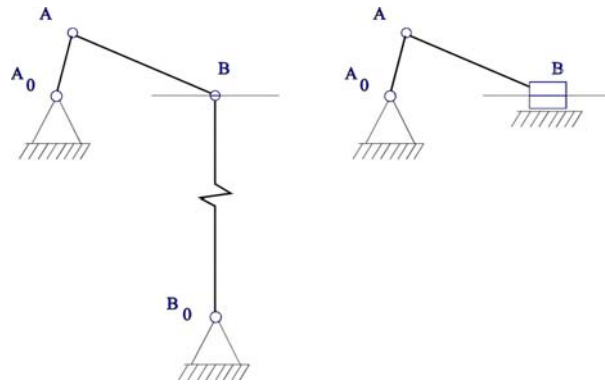


Figure 5-6 Link of Infinite Length

A grounded link of infinite length can be replaced by a slider. Since B_0B is of infinite length, pivot B in Figure 5-6 describes a straight line. Thus a crank-slider is created, best known from the combustion engine. The piston acts as the input link, the crank acts as the output link.

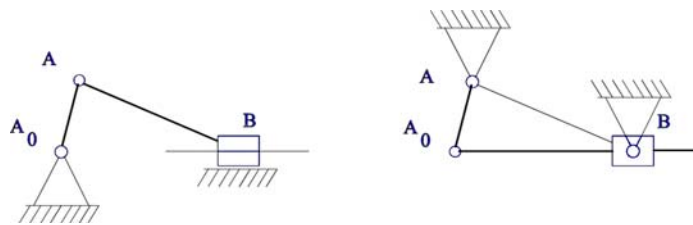


Figure 5-7 Kinematic Inversion

If another link is chosen as fundament a kinematic inversion is created. The crank slider mechanism in Figure 5-7 is inverted. Link AB becomes ground link. The slider is transformed into a pivoting slider by the inversion (a hydraulic or pneumatic cylinder).

Kinematic diagrams

Although a four bar is simple and versatile, it sometimes may be desirable and necessary to apply more complex mechanisms.

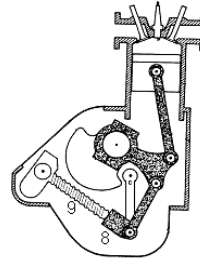


Figure 5-8 Combustion Engine with Variable Stroke

In **Figure 5-8** a piston engine with variable stroke is shown. The stroke can be varied by moving the control-nut (8) along the control-screw (9).

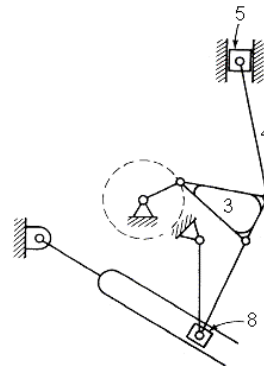


Figure 5-9 Kinematic Diagram

For analysis and synthesis purposes a schematic way of drawing is used. The **kinematic diagram** in **Figure 5-9** provides a clearer image of its function than **Figure 5-8**.

A kinematic diagram uses standard elements.

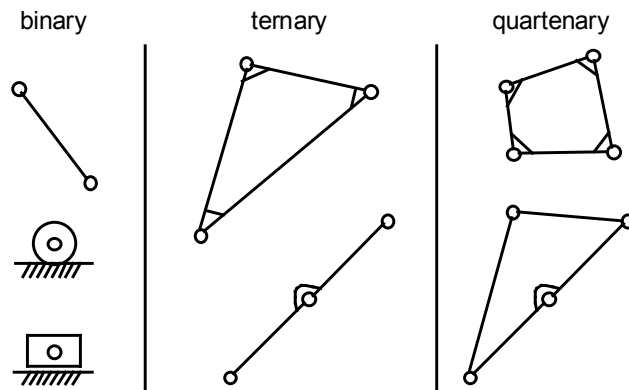


Figure 5-10 Binary, Ternary and Quaternary Links

In kinematics each element between two or more pivots is considered a rigid link. The elements are arranged according to the number of connections or joints. Thus exist: binary, ternary and quaternary links.

Different ways of notation are used. However there must be a clear distinction between a rigid multiple link and a **chain** of binary links.

Link 5 (piston in **Figure 5-8**) has a sliding connection to the ground link (the wall of the cylinder) and a pivoting connection to link 4 (the piston link). The piston is a binary link.

Link 3 has three pivoting connections to the surrounding links and is a ternary link.

On link 8 (control-nut) two pivoting joints coincide in the projected view. The third joint converts link 8 into a ternary link.

The parts of the piston engine are linked in four places to the ground link. In this case the ground link is a quaternary link.

Displaying the engine house as a link creates a chain of interconnected links. This diagram is called a **kinematic chain**. To ease generalization often all joints are drawn as pivots. Figure 5-11 shows a kinematic chain of the engine using pivots as joints

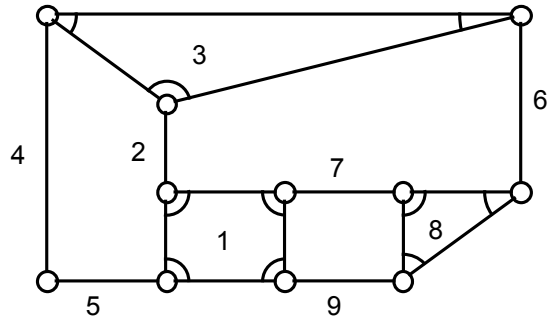


Figure 5-11 Kinematic Chain

The control nut is calibrated for a certain desired situation. Links 7,8 and 9 cannot move in this situation.

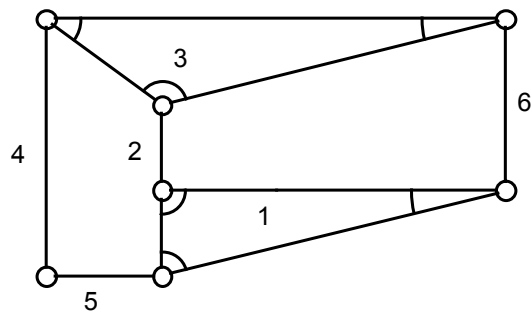


Figure 5-12 Kinematic Chain

The kinematic chain can be simplified by considering links 7,8 and 9 as part of the ground link (Figure 5-12). This chain is similar to the

universal form of the so-called Stephenson chain (Figure 5-13).

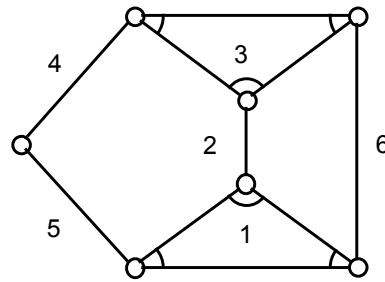


Figure 5-13 Stephenson chain

Each mechanism can be classified into a small number of types by drawing its kinematic chain. This procedure is applied when designing and analyzing mechanisms.

Example

Figure 5-14 shows the design of a prosthetic knee.

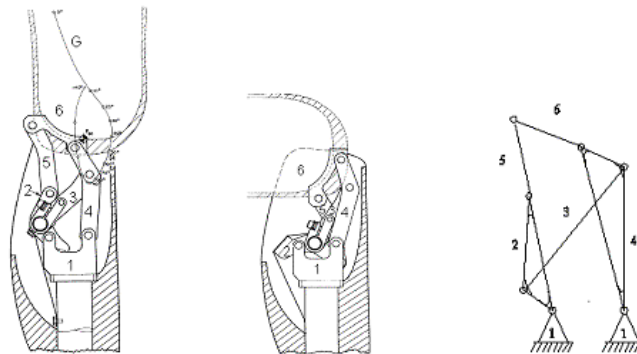


Figure 5-14 Prosthetic Knee and Kinematic Diagram

The mechanism is used to provide extra stability while standing.

A kinematic diagram can be drawn of the prosthetic knee (Figure 5-14 right). The choice of ground link is not obvious in this case. Both the upper and the lower leg move relative to the world. Considering only relative motion between upper and lower leg is relevant, one of the two can be chosen as ground link. Thus it is apparent that this is a Stephenson chain.

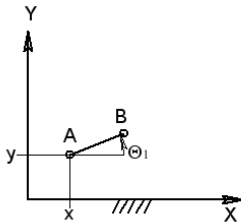


Figure 5-15

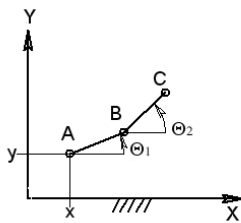


Figure 5-16

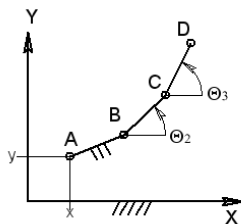


Figure 5-17

5.2 Degrees of freedom

The motion of a mechanism is fully determined, if the motion of one or more of its links is prescribed. The number of links, driving its motion, corresponds with the number of **degrees of freedom (DOF)** of the mechanism. The number of degrees of freedom determines the number of required actuators as well as the boundaries within which a body (linked to the output link) can be manipulated.

The position of link AB in Figure 5-15 is clearly fully determined by the x and y coordinates of point A and angle θ_1 . If AB can move freely in plane x - y , AB has three degrees of freedom.

Two freely moving links in the x - y plane together have six degrees of freedom (each link takes a position independent of the other). So n free moving links have $3n$ degrees of freedom.

If two links AB and BC are joined by a pivot (Figure 5-16), the x, y positions of both links are interdependent. Such a pair of links is called a dyad. Link AB can take any position. Link BC however, can only rotate around B. The open chain now only has four degrees of freedom. Apparently a pivot reduces the number of degrees of freedom by two.

Links AB, BC and CD (Figure 5-17) originally had nine degrees of freedom. Fixing one link to the world and thus creating a ground link, reduces the number of degrees of freedom by three.

If one link of a collection of n links acts as ground link, the collection has $3(n-1)$ degrees of freedom. As shown above by joining links with pivots each pivot reduces the number of degrees of freedom by two. If a collection of links is joined with f_1 pivots, the number of degrees of freedom is reduced by $2 f_1$.

This results in Grübler's equation:

$$F = 3(n - 1) - 2 f_1$$

F = number of degrees of freedom of a mechanism

n = number of links (including ground link)

f_1 = number of joints with one degree of freedom.

Two pivots in one position

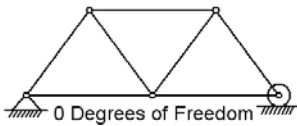


Figure 5-18

A problem arises if a number of pivots coincide. It is obvious that the truss of Figure 5-18 is statically determined and has exactly zero degrees of freedom. If the number of nodes equals the number of pivots, Grübler's equation results in $F = 12$. However, the number of joints between two links should be counted. Where three links are joined, there are two joints.

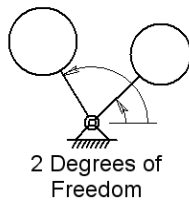


Figure 5-19

Figure 5-19- shows two links, connected with one pivot in the same position. Both links can rotate independently. Therefore the mechanism has two degrees of freedom. According to Grübler this result can only be achieved by taking two pivots into account.

If m links can pivot independently in one point, the following equation should be applied:

$$f_1 = m - 1$$

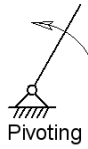
f_1 : number of joints with one degree of freedom.

m : number of links connected in one position.

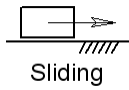
The confusion can be avoided by drawing each joint separately in a kinematic chain.

5.3 Joints

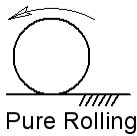
Apart from the pivot, three other elementary joints between links can be distinguished.



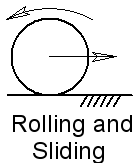
Pivoting



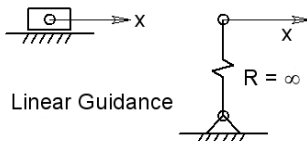
Sliding



Pure Rolling



Rolling and Sliding



Linear Guidance

Sliding along a predetermined path.

This joint is schematically drawn as a block, which slides over or through another link. The joint allows one degree of freedom (translation along the contact plane of both links) and thus is a f_1 joint.

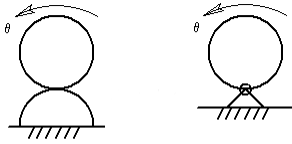
Pure rolling

This joint is schematically drawn as the pairing of two circles with different curvature (e.g. a circle and a straight line). To distinguish between a rolling/sliding joint it is possible to apply a dash. The dash indicates that there is no sliding possible in the point of contact. Rolling allows one degree of freedom thus is a f_1 joint.

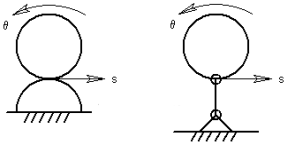
Rolling and sliding.

This joint is schematically pictured as the pairing of two circles with different curvature (e.g. a circle and a straight line). However in the point of contact rolling as well as sliding may occur. The rolling/sliding joint therefore is a f_2 joint. The various joints can also be thought of as a so-called instant equivalent, only consisting of pivoting links.

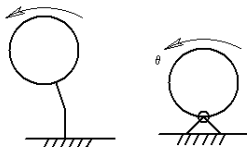
Sliding linear guidance only allows one motion in the x-direction. A link of infinite length is the instant equivalent. Rolling without sliding only rolling along the plane of contact is possible. A pivot is the instant equivalent.



Pure Rolling



Rolling and Sliding



Leaf Spring

Instant equivalents

Rolling and sliding allows two degrees of freedom at the point of contact. Apart from rolling along the plane of contact, sliding rotation can take place in any position. As instant equivalent an extra link can be placed between foundation and body.

A leaf spring as connection between two links only allows rotation (f_1 joint). Thus the instant equivalent of a leaf spring is a pivot.

In a mechanism a spring should only apply a force. A spring in a well-designed construction will not limit the degrees of freedom. So in a kinematic diagram a spring may be omitted. Sometimes it can be useful to regard the spring as a dyad, using animation software. The mechanism can be actuated by the grounded link of the dyad.

Grübler's equation equation can be further completed:

$$F = 3(n-1) - 2 f_1 - f_2$$

F : number of degrees of freedom.

n : number of links (including ground link)

f_1 : number of joints with one degree of freedom.

f_2 : number of joints with two degrees of freedom.

How to determine the degrees of freedom of a mechanism:

1. Draw a kinematic diagram of the mechanism. (In some cases use instant equivalents).
2. Number the links, starting at the ground link.
3. Define the type and number of joints.
4. Calculate the number of degrees of freedom using Grübler's equation.

Example: Degrees of freedom of a pair of gears

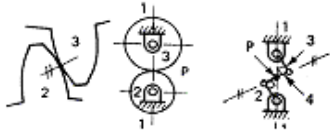


Figure 5-20

The pair of gears in Figure 5-20 consists of 3 links including the ground link. Two pivots (f_1 joints) join the gears to the ground link. The gear teeth have rolling and sliding contact (one f_2 joint). According to Grübler the mechanism has one degree of freedom. If one of the gears is being actuated the motion of the whole mechanism is determined.

The momentary equivalent of a pair of gears can be represented by a four bar, in which the pivots of the coupler are situated on the ground circle of the gears.

Example: Degrees of freedom of a belt and pulley mechanism

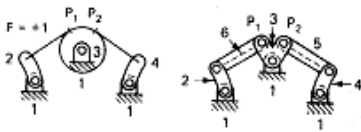


Figure 5-21

It is assumed no sliding between belt and pulley will occur (Figure 5-21). The position the belt runs on and off the wheel can be considered as momentary pivots. From the momentary equivalent mechanism the number of degrees of freedom can easily be calculated. The equivalent mechanism consists of six links joined by seven pivots (f_1). According to Grübler the mechanism has one degree of freedom.

Example

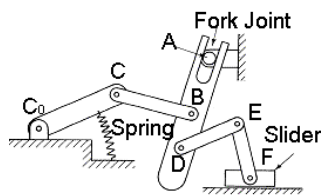


Figure 5-22

Calculate the number of degrees of freedom of the mechanism in Figure 5-22

$$n = 7$$

$$f_1 = 7 \text{ (7 pivots and 1 sliding contact)}$$

$$f_2 = 1 \text{ (the fork-joint allows rolling as well as sliding)}$$

$$F = 3(7-1) - 2*7 - 1*1 = 18 - 4 - 1 = 3$$

Of the mechanism a kinematic diagram can be drawn based upon the instant equivalents (see Figure 5-23).

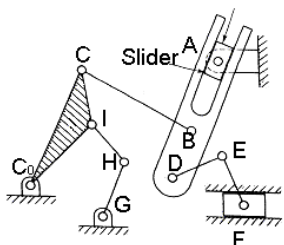


Figure 5-23

The spring is replaced by a dyad, the fork joint as a combination of a sliding contact and a pivot. The number of links increases.

$$n = 10$$

$$f_1 = 12 \text{ (10 pivots and 2 sliding contacts)}$$

$$F = 3(10-1) - 2*12 = 27 - 24 = 3$$

Is Grübler always right?

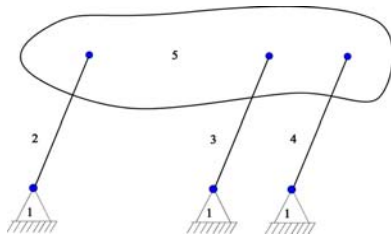


Figure 5-24

Motion of link 5 (Figure 5-24) is determined by three parallel links. Motion seems evident. According to Grübler the mechanism has 0 degrees of freedom.

$$(n = 5, f_1 = 6, F = 0).$$

However, motion depends on the fact if links 2,3 and 4 are of exactly equal length. Depending on the accuracy of production, rigidity and clearance of the joints, the mechanism will run more or less well. Definitely **not** recommended.

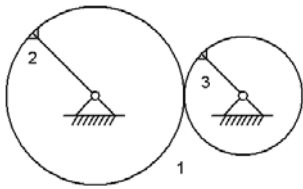


Figure 5-25

At first glance the friction wheel assembly (Figure 5-25) seems well-designed and to have one degree of freedom. According to Grübler however the construction has 0 degrees of freedom, if the wheel contact allows pure rolling only.

$$(n = 3, f_1 = 3, F = 0).$$

In case wheel contact would allow rolling and sliding the assembly has two degrees of freedom. If once more link dimensions are being taken into account it is easy to see what is wrong.

If the sum of both friction wheel radiuses is less than the distance between pivots, the wheels have no contact.

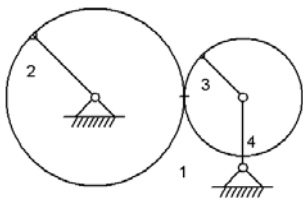


Figure 5-26

If the sum of both radiuses is greater than the distance between pivots the construction cannot be assembled.

The friction wheel transmission is only kinematically correct, if the pivot of one of the wheels can move (Figure 5-26). A spring could be applied to press both wheels together. The extra needed degree of freedom, can also be added by choosing a compliant material for the contact surface of one of the wheels (e.g. rubber surface).

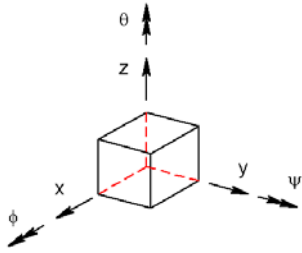


Figure 5-27

Grübler for spatial mechanisms

The position and orientation of any body is determined by six parameters: $x, y, z, \varphi, \psi, \theta$. A spatial body therefore has six degrees of freedom.

Grübler for spatial mechanisms can be formulated as follows:

$$F = (n-1) - 5f_1 - 4f_2 - 3f_3 - 2f_4 - 1f_5.$$

F : Number of degrees of freedom

n : Number of links (incl. ground).

f_1 : Number of joints with one degree of freedom.

- Line hinge (axle with double bearing)
- Leaf spring (torsionally stiff)
- Pure rolling of a cylinder.

f_2 : Number of joints with two degrees of freedom.

- Spherical contact (rolling)
- Leaf spring (torsion weak)
- Wire spring (torsion rigid)

f_3 : Number of joints with three degrees of freedom.

- Spherical pivot
- Wire spring (torsionally compliant)
- Sliding contact (e.g. x, y, θ)

f_4 : Number of joints with five degrees of freedom.

- Rolling and sliding of a cylinder.

f_5 : Number of joints with five degrees of freedom.

- Spherical contact (rolling and sliding).

Example

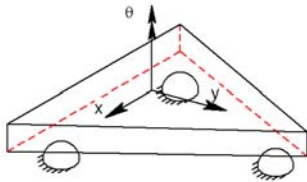


Figure 5-28

Spherical surfaces only fix one degree of freedom, if rolling and sliding is possible. The body in the figure on the left is resting on three spherical surfaces, which are part of the ground link.

$$n = 2$$

$$f_5 = 3 \text{ (rolling and sliding)}$$

$$F = 6(2-1) - 1*3 = 6-3 = 3$$

The body is fixed in the z-direction and cannot rotate around the x-axis and around the y-axis.

If the body is placed on three spheres:

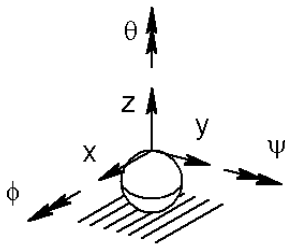


Figure 5-29

$$n = 5 \text{ (ground, three spheres and body)}$$

$$f_1 = 6 \text{ (rolling and sliding)}$$

$$F = 6(5-1) - 1*6 = 24 - 6 = 18$$

The body still has three degrees of freedom. Because it is assumed the spherical contacts allows rolling and sliding, each sphere can move freely between ground triangular body. Each sphere consequently has five degrees of freedom, resulting in 18 degrees of freedom for the whole assembly.

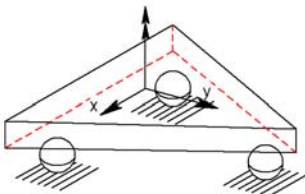


Figure 5-30

If sufficient force is present between the triangular body and ground, it seems likely no sliding will occur in each contact. Every contact now has only two rotational degrees of freedom. The number of degrees of freedom according to Grübler are:

$$n = 5 \text{ (ground, three balls and triangular body)}$$

$$f_2 = 6 \text{ (six spherical contacts, rolling, no sliding)}$$

$$F = 6(5-1) - 4*6 = 24 - 24 = 0.$$

According to Grübler the triangular body cannot possess three degrees of freedom, if rolling without sliding in all contact planes is assumed. At first glance it seems that the spheres have to roll, no matter how the body is moved. However if the diameters of the spheres are not exactly equal, rolling without sliding will only occur in a curved trajectory. As soon as the body is forced to move along a straight line, compensation will be needed for its 'innate' behavior, by allowing rotation around the z-axis in some contact points.

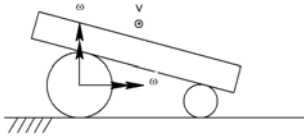


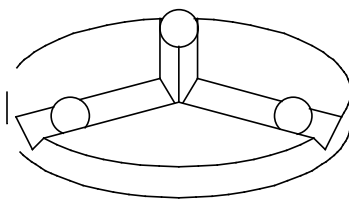
Figure 5-31

Spin around the z-axis will occur relatively easy, because a spherical contact has limited potential for a frictional torque. Spin in a contact can also be observed in case the triangular body rotates around the center line of one of the spheres.

Grübler calculates three degrees of freedom, if it is assumed in three of six contacts rotation around the z-axis is possible:

$$\begin{aligned}
 n &= 5 && \text{(ground, three spheres and body)} \\
 f_2 &= 3 && \text{(3 spherical contacts, rolling no sliding)} \\
 f_3 &= 3 && \text{(3 spherical contacts, rolling and sliding)}
 \end{aligned}$$

$$F = 6(5-1) - 4*3 - 3*3 = 24 - 12 - 9 = 3.$$

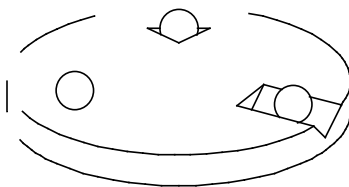


2-2-2

Figure 5-32

Accurate (re)positioning

A problem often cropping up in precision instruments is accurate (re)positioning of two bodies in respect to each other resulting in zero degrees of freedom.



3-2-1 Kelvin

Figure 5-33

If spherical contacts with rolling and sliding are applied between ground and body, according to Grübler, six of those joints should be applied. A lot of configurations are possible. Two of the most well known designs are shown on the left. The spheres are shown detached, but they need to be part of one of the two bodies. Positioning with micrometer accuracy is possible.

Various kinematic chains

Reasoning from the number of degrees of freedom needed, the number of links and the type of joints all possible kinematic chains can be determined. If only joints with one degree of freedom are desired Grüber gives:

$$f_1 = \frac{3(n-1) - F}{2}$$

F: number of degrees of freedom.

n : number of links in the mechanism (incl. ground)

f_1 : number of joints with one degree of freedom.

From the number of binary, ternary and quaternary links the number of joints results:

$$f_1 = \frac{2S_2 + 3S_3 + 4S_4}{2}$$

S_2 : Number of binary links in the mechanism

S_3 : Number of ternary links in the mechanism

S_4 : Number of quaternary links in the mechanism.

Assume:

$$n = S_2 + S_3 + S_4$$

Six bars with one degree of freedom

To determine all possible kinematic chains with six links and a single degree of freedom:

$$n = 6 \text{ and } F = 1$$

$$f_1 = 7$$

To solve:

$$\frac{2S_2 + 3S_3 + 4S_4}{2} = 7$$

$$S_2 + S_3 + S_4 = 6$$

The only solution is:

$$S_2 = 4 \text{ and } S_3 = 2 \text{ and } S_4 = 0$$

Using four binary and two ternary links, two different chains can be assembled. They are known as the Watt chain and the Stephenson chain (Figure 5-34). The Stephenson chain has two ternary links separated by a binary link. From the Watt chain two kinematic inversions can be derived. The Stephenson chain results in three kinematic inversions (Figure 5-34). The freedom of choice of the input and output link enhances the number of available configurations even more.

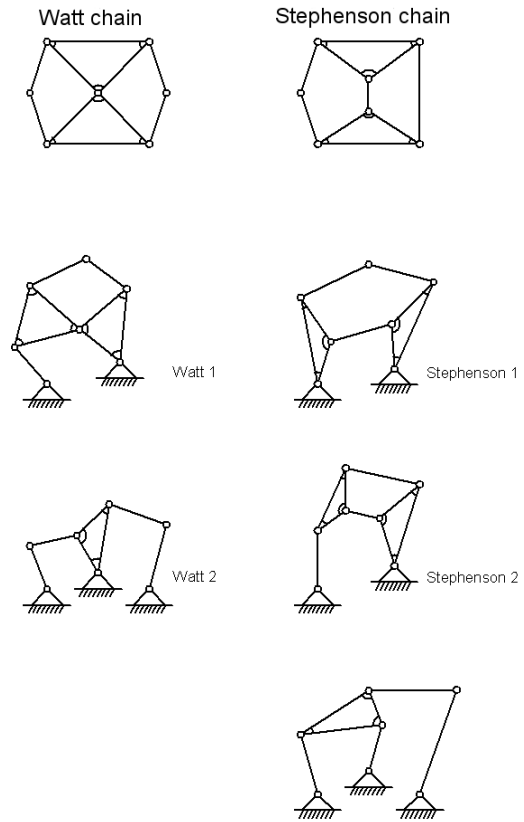


Figure 5-34 Watt chain and Stephenson chain

Instead of the pivots, other kinds of joints, which result in one degree of freedom, inserted in each chain. A few Watt chains with a sliding joint and one with a rolling joint are shown in Figure 5-35. Figure 5-35V shows a typical cam mechanism.

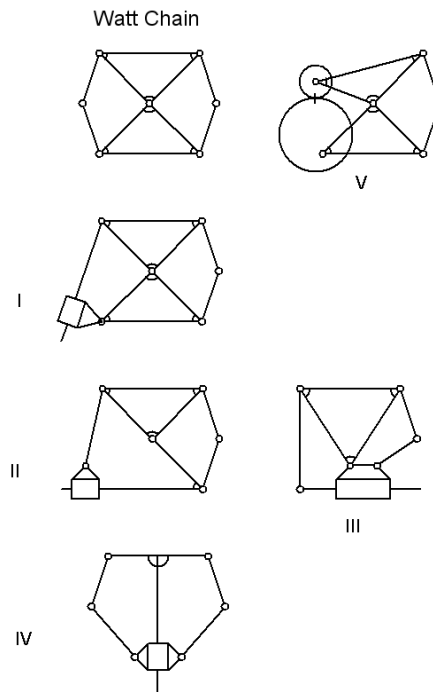


Figure 5-35 Alternative Watt Chains.

Eight bar mechanisms with one degree of freedom

Determine the number of possible kinematic chains of mechanisms with eight links and one degree of freedom.

$$n = 8 \text{ and } F = 1$$

$$f_1 = 10$$

Result: $\frac{2S_2 + 3S_3 + 4S_4}{2} = 10$

And $S_2 + S_3 + S_4 = 8$

	S_2	S_3	S_4
I	6	0	2
II	5	2	1
III	4	4	0

Three combinations of binary, ternary and quaternary links are possible. For every combination a number of chains can be drawn. The chains in which immobile parts occur are omitted.

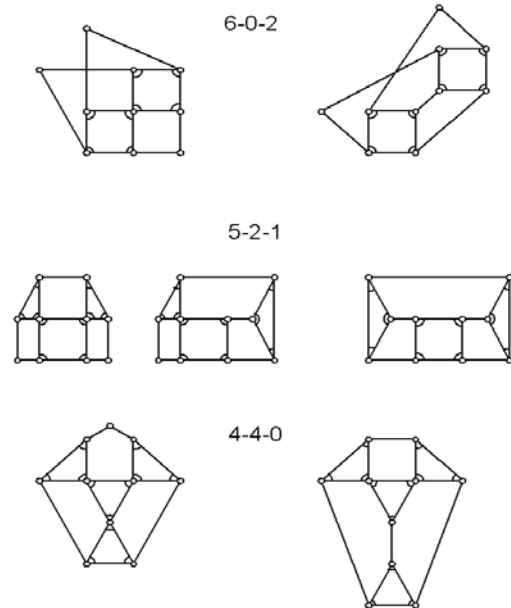
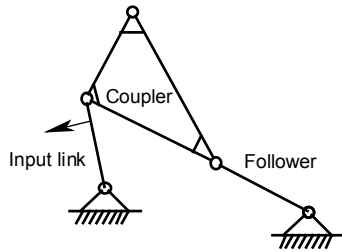


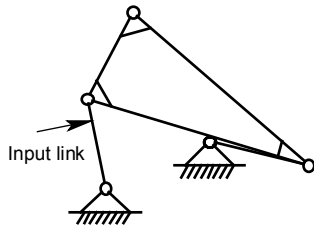
Figure 5-36 Eight Bars with one degree of Freedom

For mechanisms in which joints with two degrees of freedom occur, the number of kinematic chains can be determined in much the same way.

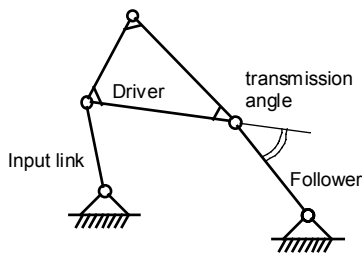
5.4 Transmission angle



A four bar mechanism has two positions it locks up. These positions are called **dead center** or **singular** positions. Both coupler and follower link are in line and if there is no inertia to pull the mechanism through, it is stuck.



Near these dead center positions the coupler has to push the follower at an ever more inefficient angle. Most of the force conducted to the follower link is normal to it and will result in ever increasing friction. As a result a mechanism can block even before it reaches its dead center position.



To evaluate the likelihood of blocking, the transmission angle is introduced. It is defined as the smallest angle between driving and following link.

Depending on the friction in the bearings used, it is sensible to prevent a mechanism from having a transmission angle that is too low. A minimum of 5 degrees is a sensible precaution.

Six bar and eight bar mechanisms have two to three combinations of driving and following links that needs watching. WATT always displays the minimum value of these transmission angles.

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