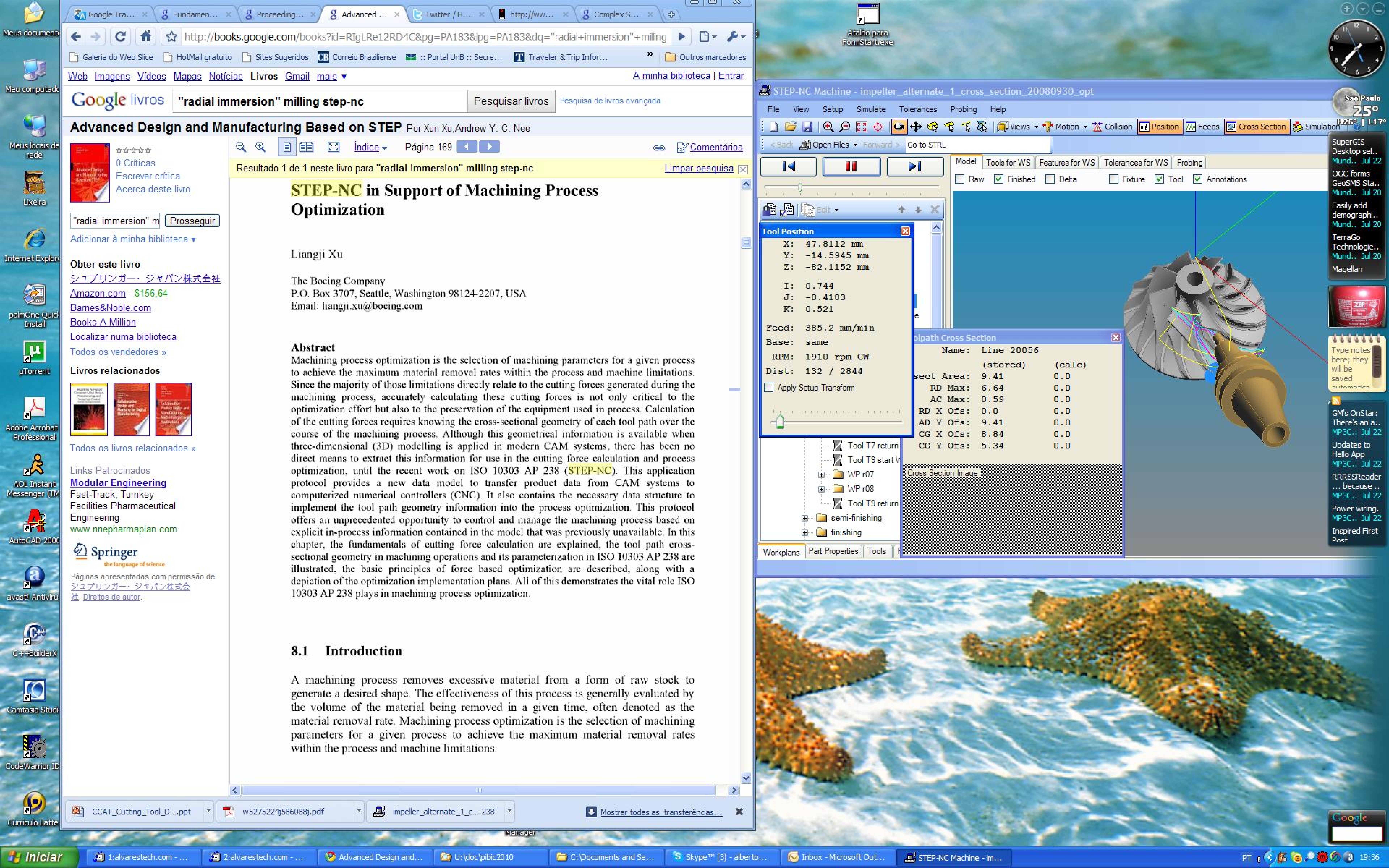

STEP-NC in Support of Machining Process Optimization

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Abstract

Machining process optimization is the selection of machining parameters for a given process to achieve the maximum material removal rates within the process and machine limitations. Since the majority of those limitations directly relate to the cutting forces generated during the machining process, accurately calculating these cutting forces is not only critical to the optimization effort but also to the preservation of the equipment used in process. Calculation of the cutting forces requires knowing the cross-sectional geometry of each tool path over the course of the machining process. Although this geometrical information is available when three-dimensional (3D) modelling is applied in modern CAM systems, there has been no direct means to extract this information for use in the cutting force calculation and process optimization, until the recent work on ISO 10303 AP 238 (STEP-NC). This application protocol provides a new data model to transfer product data from CAM systems to computerized numerical controllers (CNC). It also contains the necessary data structure to implement the tool path geometry information into the process optimization. This protocol offers an unprecedented opportunity to control and manage the machining process based on explicit in-process information contained in the model that was previously unavailable. In this chapter, the fundamentals of cutting force calculation are explained, the tool path cross-sectional geometry in machining operations and its parameterization in ISO 10303 AP 238 are illustrated, the basic principles of force based optimization are described, along with a depiction of the optimization implementation plans. All of this demonstrates the vital role ISO 10303 AP 238 plays in machining process optimization.

8.1 Introduction

A machining process removes excessive material from a form of raw stock to generate a desired shape. The effectiveness of this process is generally evaluated by the volume of the material being removed in a given time, often denoted as the material removal rate. Machining process optimization is the selection of machining parameters for a given process to achieve the maximum material removal rates within the process and machine limitations.

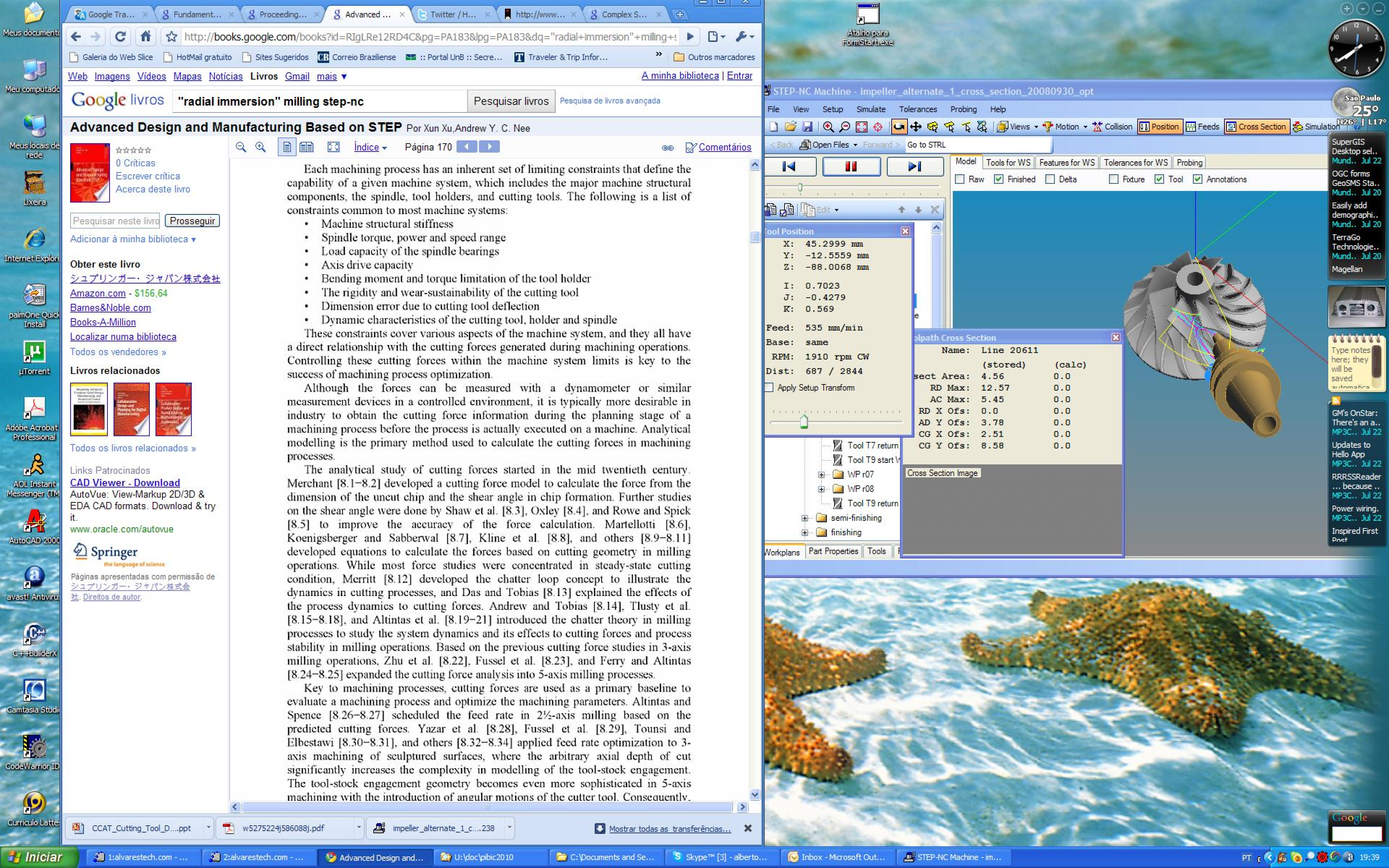
Tool Position

```
  X:  47.8112 mm
  Y:  -14.5945 mm
  Z:  -82.1152 mm

  I:  0.744
  J:  -0.4183
  K:  0.521

Feed:  385.2 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  132 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
       Name:  Line 20056
              (stored)     (calc)
sect Area:    9.41         0.0
  RD Max:     6.64         0.0
  AC Max:     0.59         0.0
RD X Ofs:     0.0          0.0
AD Y Ofs:     9.41         0.0
CG X Ofs:     8.84         0.0
CG Y Ofs:     5.34         0.0
```



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Each machining process has an inherent set of limiting constraints that define the capability of a given machine system, which includes the major machine structural components, the spindle, tool holders, and cutting tools. The following is a list of constraints common to most machine systems:

- Machine structural stiffness
- Spindle torque, power and speed range
- Load capacity of the spindle bearings
- Axis drive capacity
- Bending moment and torque limitation of the tool holder
- The rigidity and wear-sustainability of the cutting tool
- Dimension error due to cutting tool deflection
- Dynamic characteristics of the cutting tool, holder and spindle

These constraints cover various aspects of the machine system, and they all have a direct relationship with the cutting forces generated during machining operations. Controlling these cutting forces within the machine system limits is key to the success of machining process optimization.

Although the forces can be measured with a dynamometer or similar measurement devices in a controlled environment, it is typically more desirable in industry to obtain the cutting force information during the planning stage of a machining process before the process is actually executed on a machine. Analytical modelling is the primary method used to calculate the cutting forces in machining processes.

The analytical study of cutting forces started in the mid twentieth century. Merchant [8.1–8.2] developed a cutting force model to calculate the force from the dimension of the uncut chip and the shear angle in chip formation. Further studies on the shear angle were done by Shaw et al. [8.3], Oxley [8.4], and Rowe and Spick [8.5] to improve the accuracy of the force calculation. Martellotti [8.6], Koenigsberger and Sabberwal [8.7], Kline et al. [8.8], and others [8.9–8.11] developed equations to calculate the forces based on cutting geometry in milling operations. While most force studies were concentrated in steady-state cutting condition, Merritt [8.12] developed the chatter loop concept to illustrate the dynamics in cutting processes, and Das and Tobias [8.13] explained the effects of the process dynamics to cutting forces. Andrew and Tobias [8.14], Tlusty et al. [8.15–8.18], and Altintas et al. [8.19–21] introduced the chatter theory in milling processes to study the system dynamics and its effects to cutting forces and process stability in milling operations. Based on the previous cutting force studies in 3-axis milling operations, Zhu et al. [8.22], Fussel et al. [8.23], and Ferry and Altintas [8.24–8.25] expanded the cutting force analysis into 5-axis milling processes.

Key to machining processes, cutting forces are used as a primary baseline to evaluate a machining process and optimize the machining parameters. Altintas and Spence [8.26–8.27] scheduled the feed rate in 2½-axis milling based on the predicted cutting forces. Yazar et al. [8.28], Fussel et al. [8.29], Tounsi and Elbestawi [8.30–8.31], and others [8.32–8.34] applied feed rate optimization to 3-axis machining of sculptured surfaces, where the arbitrary axial depth of cut significantly increases the complexity in modelling of the tool-stock engagement. The tool-stock engagement geometry becomes even more sophisticated in 5-axis machining with the introduction of angular motions of the cutter tool. Consequently,

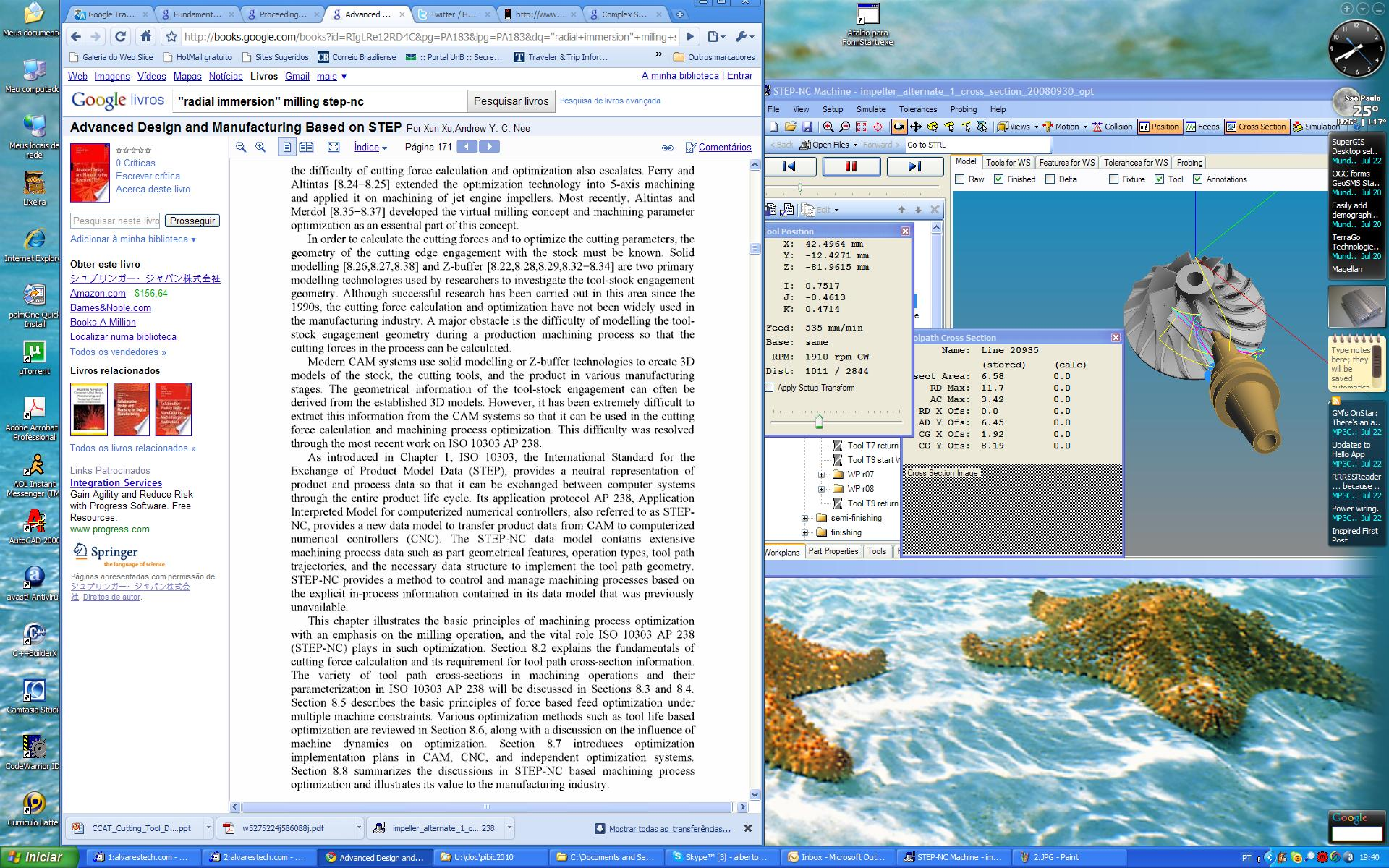
Tool Position

```
  X:  45.2999 mm
  Y:  -12.5559 mm
  Z:  -88.0068 mm

  I:  0.7023
  J:  -0.4279
  K:  0.569

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  687 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
        Name:  Line 20611
               (stored)     (calc)
Sect Area:     4.56         0.0
   RD Max:     12.57        0.0
   AC Max:     5.45         0.0
 RD X Ofs:     0.0          0.0
 AD Y Ofs:     3.78         0.0
 CG X Ofs:     2.51         0.0
 CG Y Ofs:     8.58         0.0
```



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0 Críticas

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the difficulty of cutting force calculation and optimization also escalates. Ferry and Altintas [8.24–8.25] extended the optimization technology into 5-axis machining and applied it on machining of jet engine impellers. Most recently, Altintas and Merdol [8.35–8.37] developed the virtual milling concept and machining parameter optimization as an essential part of this concept.

In order to calculate the cutting forces and to optimize the cutting parameters, the geometry of the cutting edge engagement with the stock must be known. Solid modelling [8.26,8.27,8.38] and Z-buffer [8.22,8.28,8.29,8.32–8.34] are two primary modelling technologies used by researchers to investigate the tool-stock engagement geometry. Although successful research has been carried out in this area since the 1990s, the cutting force calculation and optimization have not been widely used in the manufacturing industry. A major obstacle is the difficulty of modelling the tool-stock engagement geometry during a production machining process so that the cutting forces in the process can be calculated.

Modern CAM systems use solid modelling or Z-buffer technologies to create 3D models of the stock, the cutting tools, and the product in various manufacturing stages. The geometrical information of the tool-stock engagement can often be derived from the established 3D models. However, it has been extremely difficult to extract this information from the CAM systems so that it can be used in the cutting force calculation and machining process optimization. This difficulty was resolved through the most recent work on ISO 10303 AP 238.

As introduced in Chapter 1, ISO 10303, the International Standard for the Exchange of Product Model Data (STEP), provides a neutral representation of product and process data so that it can be exchanged between computer systems through the entire product life cycle. Its application protocol AP 238, Application Interpreted Model for computerized numerical controllers, also referred to as STEP-NC, provides a new data model to transfer product data from CAM to computerized numerical controllers (CNC). The STEP-NC data model contains extensive machining process data such as part geometrical features, operation types, tool path trajectories, and the necessary data structure to implement the tool path geometry. STEP-NC provides a method to control and manage machining processes based on the explicit in-process information contained in its data model that was previously unavailable.

This chapter illustrates the basic principles of machining process optimization with an emphasis on the milling operation, and the vital role ISO 10303 AP 238 (STEP-NC) plays in such optimization. Section 8.2 explains the fundamentals of cutting force calculation and its requirement for tool path cross-section information. The variety of tool path cross-sections in machining operations and their parameterization in ISO 10303 AP 238 will be discussed in Sections 8.3 and 8.4. Section 8.5 describes the basic principles of force based feed optimization under multiple machine constraints. Various optimization methods such as tool life based optimization are reviewed in Section 8.6, along with a discussion on the influence of machine dynamics on optimization. Section 8.7 introduces optimization implementation plans in CAM, CNC, and independent optimization systems. Section 8.8 summarizes the discussions in STEP-NC based machining process optimization and illustrates its value to the manufacturing industry.

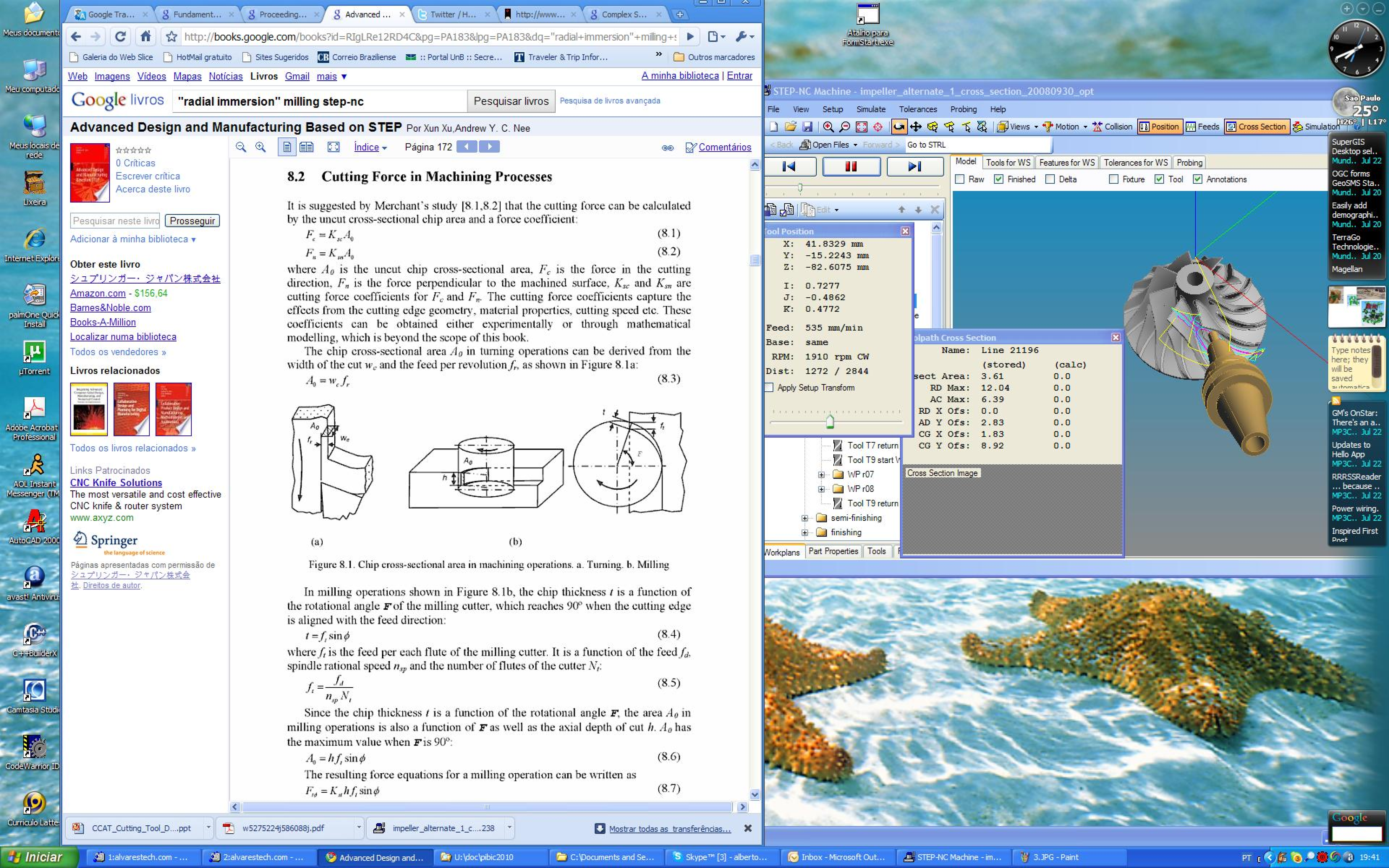
Tool Position

```
 X:  42.4964 mm
 Y:  -12.4271 mm
 Z:  -81.9615 mm

 I:  0.7517
 J:  -0.4613
 K:  0.4714

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  1011 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
      Name:  Line 20935
             (stored)    (calc)
Sect Area:   6.58        0.0
   RD Max:   11.7        0.0
   AC Max:   3.42        0.0
 RD X Ofs:   0.0         0.0
 AD Y Ofs:   6.45        0.0
 CG X Ofs:   1.92        0.0
 CG Y Ofs:   8.19        0.0
```



8.2 Cutting Force in Machining Processes

It is suggested by Merchant's study [8.1,8.2] that the cutting force can be calculated by the uncut cross-sectional chip area and a force coefficient:

$$F_c = K_{sc}A_0 \qquad (8.1)$$

$$F_n = K_{sn}A_0 \qquad (8.2)$$

where A_0 is the uncut chip cross-sectional area, F_c is the force in the cutting direction, F_n is the force perpendicular to the machined surface, K_{sc} and K_{sn} are cutting force coefficients for F_c and F_n. The cutting force coefficients capture the effects from the cutting edge geometry, material properties, cutting speed etc. These coefficients can be obtained either experimentally or through mathematical modelling, which is beyond the scope of this book.

The chip cross-sectional area A_0 in turning operations can be derived from the width of the cut w_c and the feed per revolution f_r, as shown in Figure 8.1a:

$$A_0 = w_c f_r \qquad (8.3)$$

(a) (b)

Figure 8.1. Chip cross-sectional area in machining operations. a. Turning. b. Milling

In milling operations shown in Figure 8.1b, the chip thickness t is a function of the rotational angle $\boldsymbol{F}$ of the milling cutter, which reaches 90° when the cutting edge is aligned with the feed direction:

$$t = f_t \sin\phi \qquad (8.4)$$

where f_t is the feed per each flute of the milling cutter. It is a function of the feed f_d, spindle rational speed n_{sp} and the number of flutes of the cutter N_t:

$$f_t = \frac{f_d}{n_{sp} N_t} \qquad (8.5)$$

Since the chip thickness t is a function of the rotational angle $\boldsymbol{F}$, the area A_0 in milling operations is also a function of $\boldsymbol{F}$ as well as the axial depth of cut h. A_0 has the maximum value when $\boldsymbol{F}$ is 90°:

$$A_0 = h f_t \sin\phi \qquad (8.6)$$

The resulting force equations for a milling operation can be written as

$$F_{t\phi} = K_{st} h f_t \sin\phi \qquad (8.7)$$

Tool Position

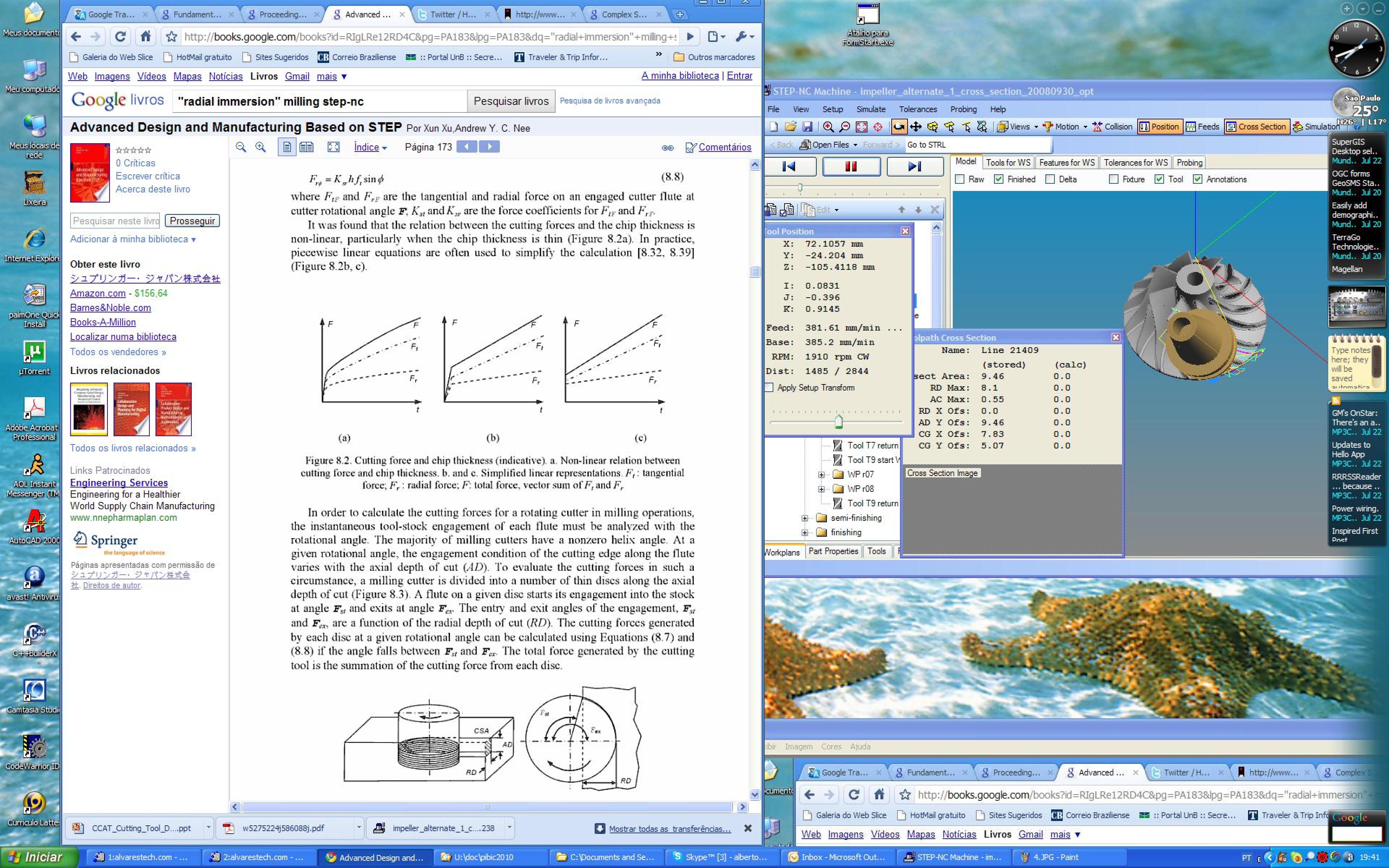
```
X:  41.8329 mm
Y:  -15.2243 mm
Z:  -82.6075 mm

I:  0.7277
J:  -0.4862
K:  0.4772

Feed:  535 mm/min
Base:  same
RPM:  1910 rpm CW
Dist:  1272 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
         Name:  Line 21196
                (stored)    (calc)
sect Area:  3.61        0.0
  RD Max:  12.04       0.0
  AC Max:  6.39        0.0
RD X Ofs:  0.0         0.0
AD Y Ofs:  2.83        0.0
CG X Ofs:  1.83        0.0
CG Y Ofs:  8.92        0.0
```

☐ Raw ☑ Finished ☐ Delta ☐ Fixture ☑ Tool ☑ Annotations



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$$F_{r\phi} = K_{sr} h f_t \sin\phi \qquad (8.8)$$

where F_{tF} and F_{rF} are the tangential and radial force on an engaged cutter flute at cutter rotational angle $\boldsymbol{F}$, K_{st} and K_{sr} are the force coefficients for F_{tF} and F_{rF}.

It was found that the relation between the cutting forces and the chip thickness is non-linear, particularly when the chip thickness is thin (Figure 8.2a). In practice, piecewise linear equations are often used to simplify the calculation [8.32, 8.39] (Figure 8.2b, c).

Figure 8.2. Cutting force and chip thickness (indicative). a. Non-linear relation between cutting force and chip thickness. b. and c. Simplified linear representations. F_t : tangential force; F_r : radial force; F: total force, vector sum of F_t and F_r

In order to calculate the cutting forces for a rotating cutter in milling operations, the instantaneous tool-stock engagement of each flute must be analyzed with the rotational angle. The majority of milling cutters have a nonzero helix angle. At a given rotational angle, the engagement condition of the cutting edge along the flute varies with the axial depth of cut (*AD*). To evaluate the cutting forces in such a circumstance, a milling cutter is divided into a number of thin discs along the axial depth of cut (Figure 8.3). A flute on a given disc starts its engagement into the stock at angle $\boldsymbol{F}_{st}$ and exits at angle $\boldsymbol{F}_{ex}$. The entry and exit angles of the engagement, $\boldsymbol{F}_{st}$ and $\boldsymbol{F}_{ex}$, are a function of the radial depth of cut (*RD*). The cutting forces generated by each disc at a given rotational angle can be calculated using Equations (8.7) and (8.8) if the angle falls between $\boldsymbol{F}_{st}$ and $\boldsymbol{F}_{ex}$. The total force generated by the cutting tool is the summation of the cutting force from each disc.

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STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

Tool Position

```
X:   72.1057 mm
Y:   -24.204 mm
Z:   -105.4118 mm

I:   0.0831
J:   -0.396
K:   0.9145

Feed:  381.61 mm/min ...
Base:  385.2 mm/min
RPM:  1910 rpm CW
Dist:  1485 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
          Name:  Line 21409
                 (stored)    (calc)
Sect Area:  9.46        0.0
   RD Max:  8.1         0.0
   AC Max:  0.55        0.0
 RD X Ofs:  0.0         0.0
 AD Y Ofs:  9.46        0.0
 CG X Ofs:  7.83        0.0
 CG Y Ofs:  5.07        0.0
```

Google Tra... Fundament... Proceeding... Advanced ... Twitter / H... http://www... Complex S
http://books.google.com/books?id=RIgLRe12RD4C&pg=PA183&lpg=PA183&dq="radial+immersion"+
Galeria do Web Slice HotMail gratuito Sites Sugeridos Correio Braziliense :: Portal UnB :: Secre... Traveler & Trip Info
Web Imagens Vídeos Mapas Notícias Livros Gmail mais

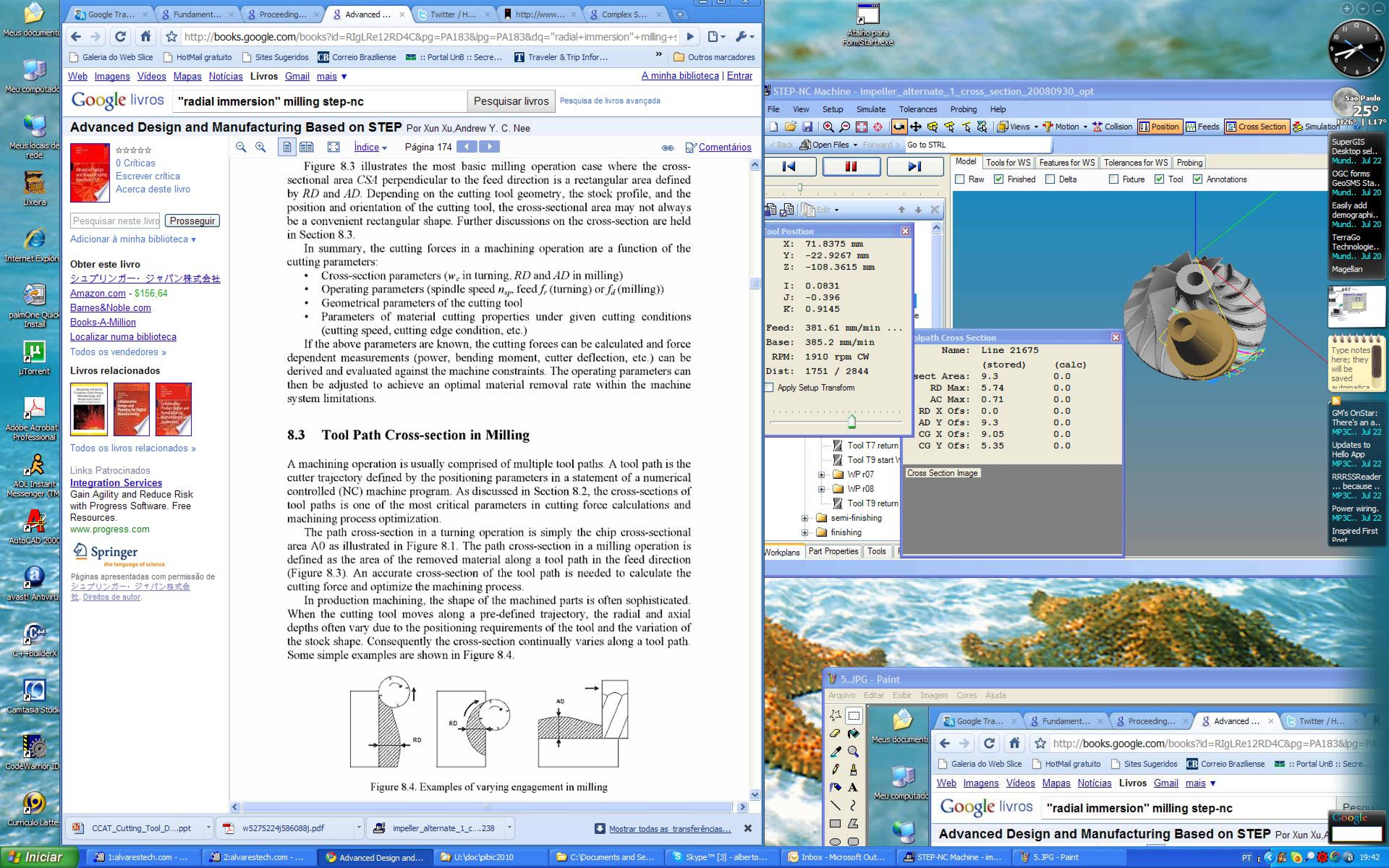


Figure 8.3 illustrates the most basic milling operation case where the cross-sectional area *CSA* perpendicular to the feed direction is a rectangular area defined by *RD* and *AD*. Depending on the cutting tool geometry, the stock profile, and the position and orientation of the cutting tool, the cross-sectional area may not always be a convenient rectangular shape. Further discussions on the cross-section are held in Section 8.3.

In summary, the cutting forces in a machining operation are a function of the cutting parameters:

- Cross-section parameters (w_c in turning, *RD* and *AD* in milling)
- Operating parameters (spindle speed n_{sp}, feed f_r (turning) or f_d (milling))
- Geometrical parameters of the cutting tool
- Parameters of material cutting properties under given cutting conditions (cutting speed, cutting edge condition, etc.)

If the above parameters are known, the cutting forces can be calculated and force dependent measurements (power, bending moment, cutter deflection, etc.) can be derived and evaluated against the machine constraints. The operating parameters can then be adjusted to achieve an optimal material removal rate within the machine system limitations.

8.3 Tool Path Cross-section in Milling

A machining operation is usually comprised of multiple tool paths. A tool path is the cutter trajectory defined by the positioning parameters in a statement of a numerical controlled (NC) machine program. As discussed in Section 8.2, the cross-sections of tool paths is one of the most critical parameters in cutting force calculations and machining process optimization.

The path cross-section in a turning operation is simply the chip cross-sectional area A0 as illustrated in Figure 8.1. The path cross-section in a milling operation is defined as the area of the removed material along a tool path in the feed direction (Figure 8.3). An accurate cross-section of the tool path is needed to calculate the cutting force and optimize the machining process.

In production machining, the shape of the machined parts is often sophisticated. When the cutting tool moves along a pre-defined trajectory, the radial and axial depths often vary due to the positioning requirements of the tool and the variation of the stock shape. Consequently the cross-section continually varies along a tool path. Some simple examples are shown in Figure 8.4.

Figure 8.4. Examples of varying engagement in milling

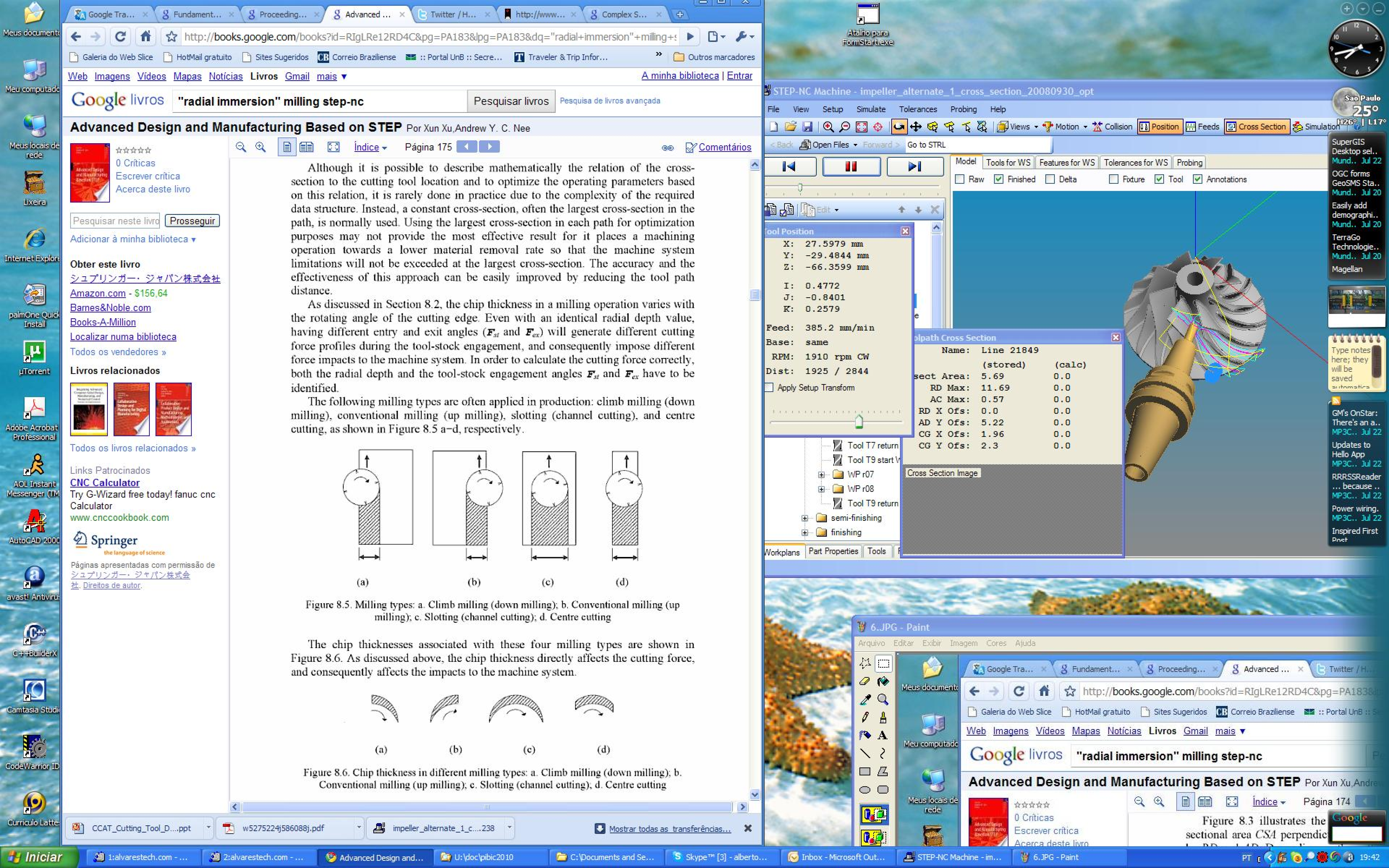
```
 X:  71.8375 mm
 Y:  -22.9267 mm
 Z:  -108.3615 mm

 I:  0.0831
 J:  -0.396
 K:  0.9145

Feed:  381.61 mm/min ...
Base:  385.2 mm/min
 RPM:  1910 rpm CW
Dist:  1751 / 2844
```

☐ Apply Setup Transform

```
          Name:  Line 21675
                 (stored)     (calc)
  sect Area:     9.3          0.0
     RD Max:     5.74         0.0
     AC Max:     0.71         0.0
   RD X Ofs:     0.0          0.0
   AD Y Ofs:     9.3          0.0
   CG X Ofs:     9.05         0.0
   CG Y Ofs:     5.35         0.0
```



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Although it is possible to describe mathematically the relation of the cross-section to the cutting tool location and to optimize the operating parameters based on this relation, it is rarely done in practice due to the complexity of the required data structure. Instead, a constant cross-section, often the largest cross-section in the path, is normally used. Using the largest cross-section in each path for optimization purposes may not provide the most effective result for it places a machining operation towards a lower material removal rate so that the machine system limitations will not be exceeded at the largest cross-section. The accuracy and the effectiveness of this approach can be easily improved by reducing the tool path distance.

As discussed in Section 8.2, the chip thickness in a milling operation varies with the rotating angle of the cutting edge. Even with an identical radial depth value, having different entry and exit angles (F_{st} and F_{ex}) will generate different cutting force profiles during the tool-stock engagement, and consequently impose different force impacts to the machine system. In order to calculate the cutting force correctly, both the radial depth and the tool-stock engagement angles F_{st} and F_{ex} have to be identified.

The following milling types are often applied in production: climb milling (down milling), conventional milling (up milling), slotting (channel cutting), and centre cutting, as shown in Figure 8.5 a–d, respectively.

(a) (b) (c) (d)

Figure 8.5. Milling types: a. Climb milling (down milling); b. Conventional milling (up milling); c. Slotting (channel cutting); d. Centre cutting

The chip thicknesses associated with these four milling types are shown in Figure 8.6. As discussed above, the chip thickness directly affects the cutting force, and consequently affects the impacts to the machine system.

(a) (b) (c) (d)

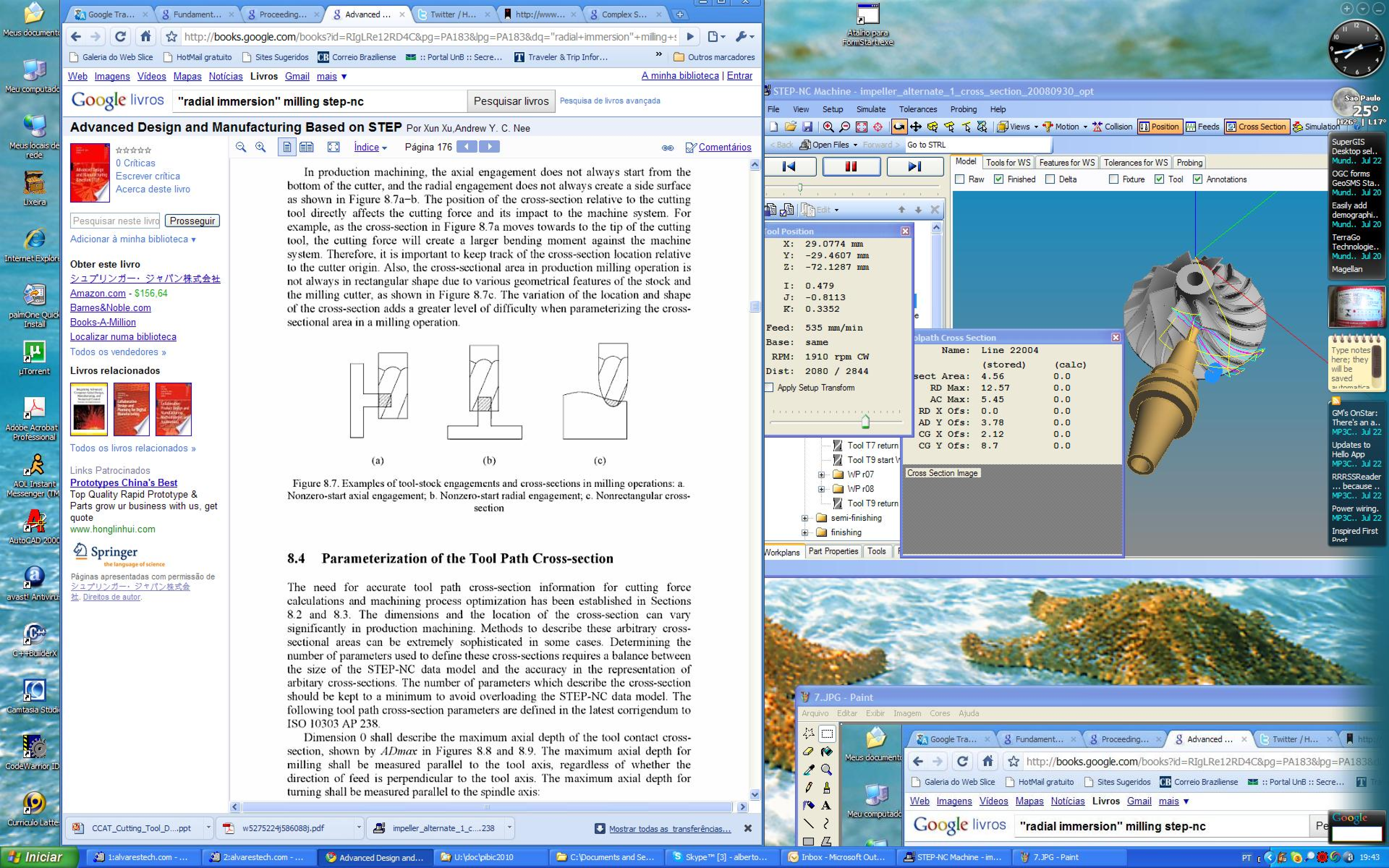
Figure 8.6. Chip thickness in different milling types: a. Climb milling (down milling); b. Conventional milling (up milling); c. Slotting (channel cutting); d. Centre cutting

```
X:  27.5979 mm
Y:  -29.4844 mm
Z:  -66.3599 mm

I:  0.4772
J:  -0.8401
K:  0.2579

Feed:  385.2 mm/min
Base:  same
RPM:  1910 rpm CW
Dist:  1925 / 2844
```

```
      Name:  Line 21849
              (stored)     (calc)
sect Area:    5.69         0.0
   RD Max:    11.69        0.0
   AC Max:    0.57         0.0
 RD X Ofs:    0.0          0.0
 AD Y Ofs:    5.22         0.0
 CG X Ofs:    1.96         0.0
 CG Y Ofs:    2.3          0.0
```



In production machining, the axial engagement does not always start from the bottom of the cutter, and the radial engagement does not always create a side surface as shown in Figure 8.7a–b. The position of the cross-section relative to the cutting tool directly affects the cutting force and its impact to the machine system. For example, as the cross-section in Figure 8.7a moves towards to the tip of the cutting tool, the cutting force will create a larger bending moment against the machine system. Therefore, it is important to keep track of the cross-section location relative to the cutter origin. Also, the cross-sectional area in production milling operation is not always in rectangular shape due to various geometrical features of the stock and the milling cutter, as shown in Figure 8.7c. The variation of the location and shape of the cross-section adds a greater level of difficulty when parameterizing the cross-sectional area in a milling operation.

(a) (b) (c)

Figure 8.7. Examples of tool-stock engagements and cross-sections in milling operations: a. Nonzero-start axial engagement; b. Nonzero-start radial engagement; c. Nonrectangular cross-section

8.4 Parameterization of the Tool Path Cross-section

The need for accurate tool path cross-section information for cutting force calculations and machining process optimization has been established in Sections 8.2 and 8.3. The dimensions and the location of the cross-section can vary significantly in production machining. Methods to describe these arbitrary cross-sectional areas can be extremely sophisticated in some cases. Determining the number of parameters used to define these cross-sections requires a balance between the size of the STEP-NC data model and the accuracy in the representation of arbitary cross-sections. The number of parameters which describe the cross-section should be kept to a minimum to avoid overloading the STEP-NC data model. The following tool path cross-section parameters are defined in the latest corrigendum to ISO 10303 AP 238.

Dimension 0 shall describe the maximum axial depth of the tool contact cross-section, shown by *ADmax* in Figures 8.8 and 8.9. The maximum axial depth for milling shall be measured parallel to the tool axis, regardless of whether the direction of feed is perpendicular to the tool axis. The maximum axial depth for turning shall be measured parallel to the spindle axis:

X: 29.0774 mm
Y: -29.4607 mm
Z: -72.1287 mm

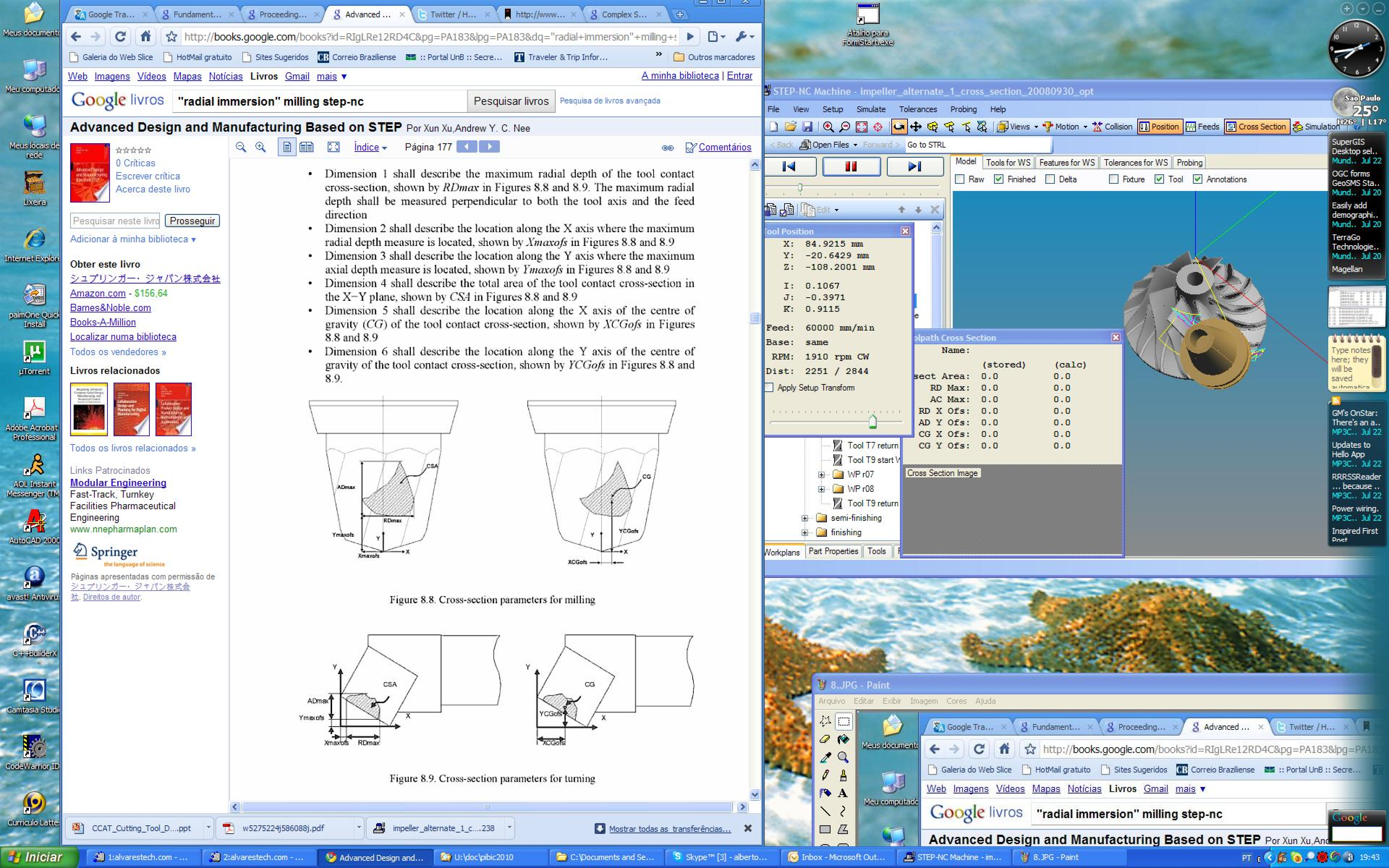
I: 0.479
J: -0.8113
K: 0.3352

Feed: 535 mm/min
Base: same
RPM: 1910 rpm CW
Dist: 2080 / 2844

☐ Apply Setup Transform

Name: Line 22004

	(stored)	(calc)
sect Area:	4.56	0.0
RD Max:	12.57	0.0
AC Max:	5.45	0.0
RD X Ofs:	0.0	0.0
AD Y Ofs:	3.78	0.0
CG X Ofs:	2.12	0.0
CG Y Ofs:	8.7	0.0



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- Dimension 1 shall describe the maximum radial depth of the tool contact cross-section, shown by *RDmax* in Figures 8.8 and 8.9. The maximum radial depth shall be measured perpendicular to both the tool axis and the feed direction
- Dimension 2 shall describe the location along the X axis where the maximum radial depth measure is located, shown by *Xmaxofs* in Figures 8.8 and 8.9
- Dimension 3 shall describe the location along the Y axis where the maximum axial depth measure is located, shown by *Ymaxofs* in Figures 8.8 and 8.9
- Dimension 4 shall describe the total area of the tool contact cross-section in the X−Y plane, shown by *CSA* in Figures 8.8 and 8.9
- Dimension 5 shall describe the location along the X axis of the centre of gravity (*CG*) of the tool contact cross-section, shown by *XCGofs* in Figures 8.8 and 8.9
- Dimension 6 shall describe the location along the Y axis of the centre of gravity of the tool contact cross-section, shown by *YCGofs* in Figures 8.8 and 8.9.

Figure 8.8. Cross-section parameters for milling

Figure 8.9. Cross-section parameters for turning

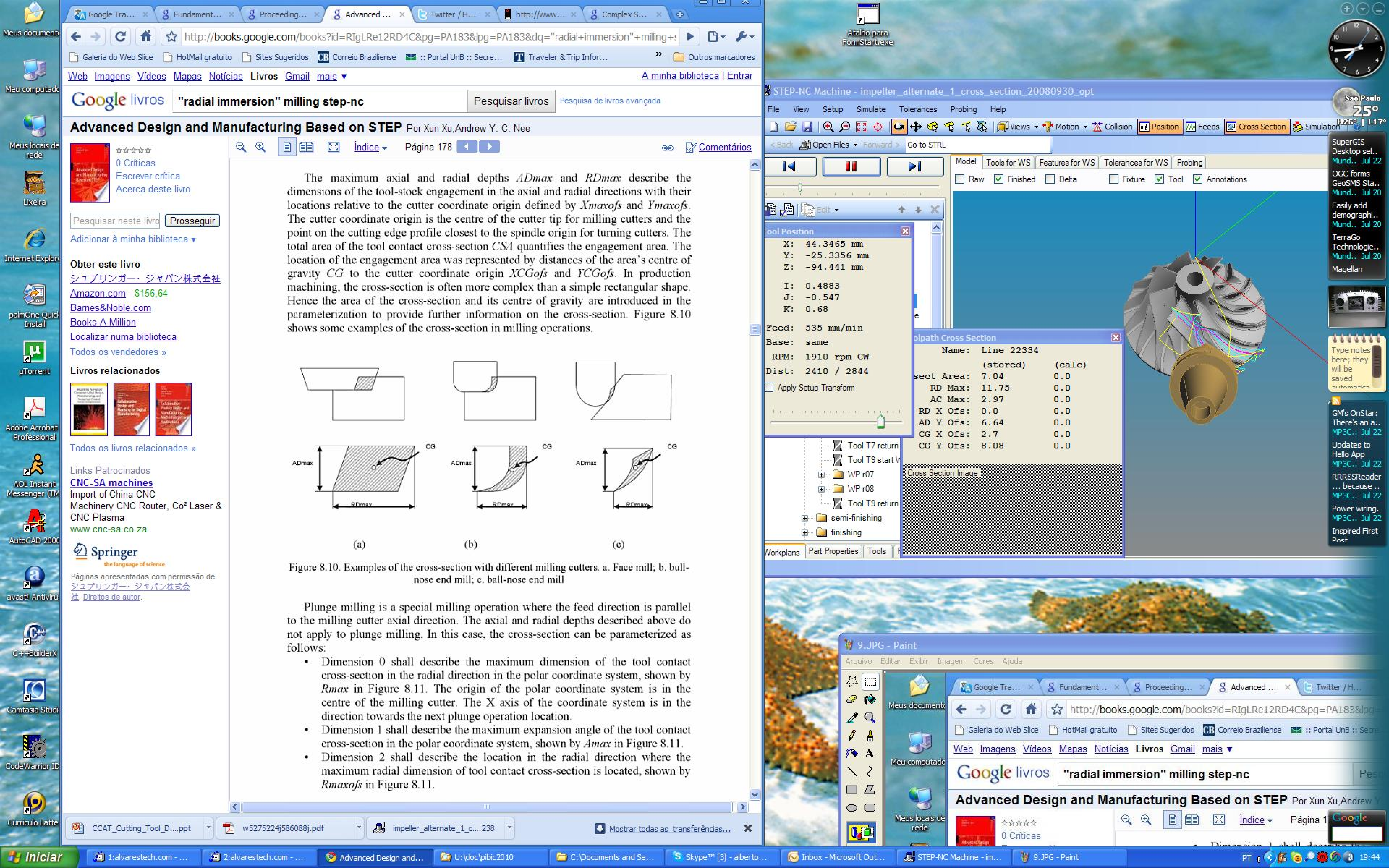
```
X:  84.9215 mm
Y:  -20.6429 mm
Z:  -108.2001 mm

I:  0.1067
J:  -0.3971
K:  0.9115

Feed:  60000 mm/min
Base:  same
RPM:  1910 rpm CW
Dist:  2251 / 2844
```

☐ Apply Setup Transform

```
        Name:
                 (stored)     (calc)
sect Area:  0.0          0.0
   RD Max:  0.0          0.0
   AC Max:  0.0          0.0
 RD X Ofs:  0.0          0.0
 AD Y Ofs:  0.0          0.0
 CG X Ofs:  0.0          0.0
 CG Y Ofs:  0.0          0.0
```



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The maximum axial and radial depths *ADmax* and *RDmax* describe the dimensions of the tool-stock engagement in the axial and radial directions with their locations relative to the cutter coordinate origin defined by *Xmaxofs* and *Ymaxofs*. The cutter coordinate origin is the centre of the cutter tip for milling cutters and the point on the cutting edge profile closest to the spindle origin for turning cutters. The total area of the tool contact cross-section *CSA* quantifies the engagement area. The location of the engagement area was represented by distances of the area's centre of gravity *CG* to the cutter coordinate origin *XCGofs* and *YCGofs*. In production machining, the cross-section is often more complex than a simple rectangular shape. Hence the area of the cross-section and its centre of gravity are introduced in the parameterization to provide further information on the cross-section. Figure 8.10 shows some examples of the cross-section in milling operations.

Figure 8.10. Examples of the cross-section with different milling cutters. a. Face mill; b. bull-nose end mill; c. ball-nose end mill

Plunge milling is a special milling operation where the feed direction is parallel to the milling cutter axial direction. The axial and radial depths described above do not apply to plunge milling. In this case, the cross-section can be parameterized as follows:

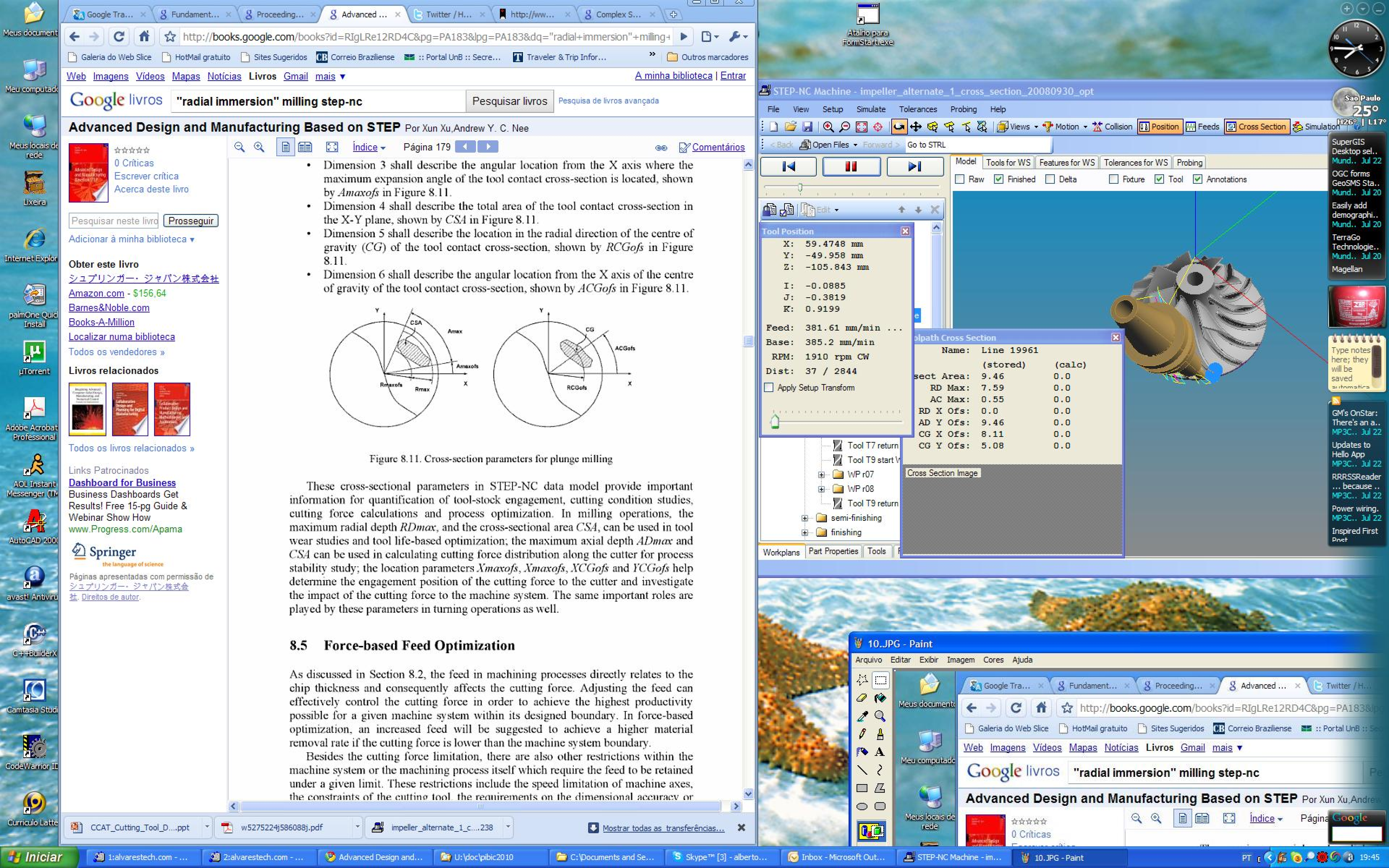
- Dimension 0 shall describe the maximum dimension of the tool contact cross-section in the radial direction in the polar coordinate system, shown by *Rmax* in Figure 8.11. The origin of the polar coordinate system is in the centre of the milling cutter. The X axis of the coordinate system is in the direction towards the next plunge operation location.
- Dimension 1 shall describe the maximum expansion angle of the tool contact cross-section in the polar coordinate system, shown by *Amax* in Figure 8.11.
- Dimension 2 shall describe the location in the radial direction where the maximum radial dimension of tool contact cross-section is located, shown by *Rmaxofs* in Figure 8.11.

```
X:  44.3465 mm
Y:  -25.3356 mm
Z:  -94.441 mm

I:  0.4883
J:  -0.547
K:  0.68

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2410 / 2844
```

```
      Name:  Line 22334
             (stored)    (calc)
sect Area:   7.04        0.0
   RD Max:   11.75       0.0
   AC Max:   2.97        0.0
 RD X Ofs:   0.0         0.0
 AD Y Ofs:   6.64        0.0
 CG X Ofs:   2.7         0.0
 CG Y Ofs:   8.08        0.0
```



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- Dimension 3 shall describe the angular location from the X axis where the maximum expansion angle of the tool contact cross-section is located, shown by *Amaxofs* in Figure 8.11.
- Dimension 4 shall describe the total area of the tool contact cross-section in the X-Y plane, shown by *CSA* in Figure 8.11.
- Dimension 5 shall describe the location in the radial direction of the centre of gravity (*CG*) of the tool contact cross-section, shown by *RCGofs* in Figure 8.11.
- Dimension 6 shall describe the angular location from the X axis of the centre of gravity of the tool contact cross-section, shown by *ACGofs* in Figure 8.11.

Figure 8.11. Cross-section parameters for plunge milling

These cross-sectional parameters in STEP-NC data model provide important information for quantification of tool-stock engagement, cutting condition studies, cutting force calculations and process optimization. In milling operations, the maximum radial depth *RDmax*, and the cross-sectional area *CSA*, can be used in tool wear studies and tool life-based optimization; the maximum axial depth *ADmax* and *CSA* can be used in calculating cutting force distribution along the cutter for process stability study; the location parameters *Xmaxofs*, *Xmaxofs*, *XCGofs* and *YCGofs* help determine the engagement position of the cutting force to the cutter and investigate the impact of the cutting force to the machine system. The same important roles are played by these parameters in turning operations as well.

8.5 Force-based Feed Optimization

As discussed in Section 8.2, the feed in machining processes directly relates to the chip thickness and consequently affects the cutting force. Adjusting the feed can effectively control the cutting force in order to achieve the highest productivity possible for a given machine system within its designed boundary. In force-based optimization, an increased feed will be suggested to achieve a higher material removal rate if the cutting force is lower than the machine system boundary.

Besides the cutting force limitation, there are also other restrictions within the machine system or the machining process itself which require the feed to be retained under a given limit. These restrictions include the speed limitation of machine axes, the constraints of the cutting tool, the requirements on the dimensional accuracy or

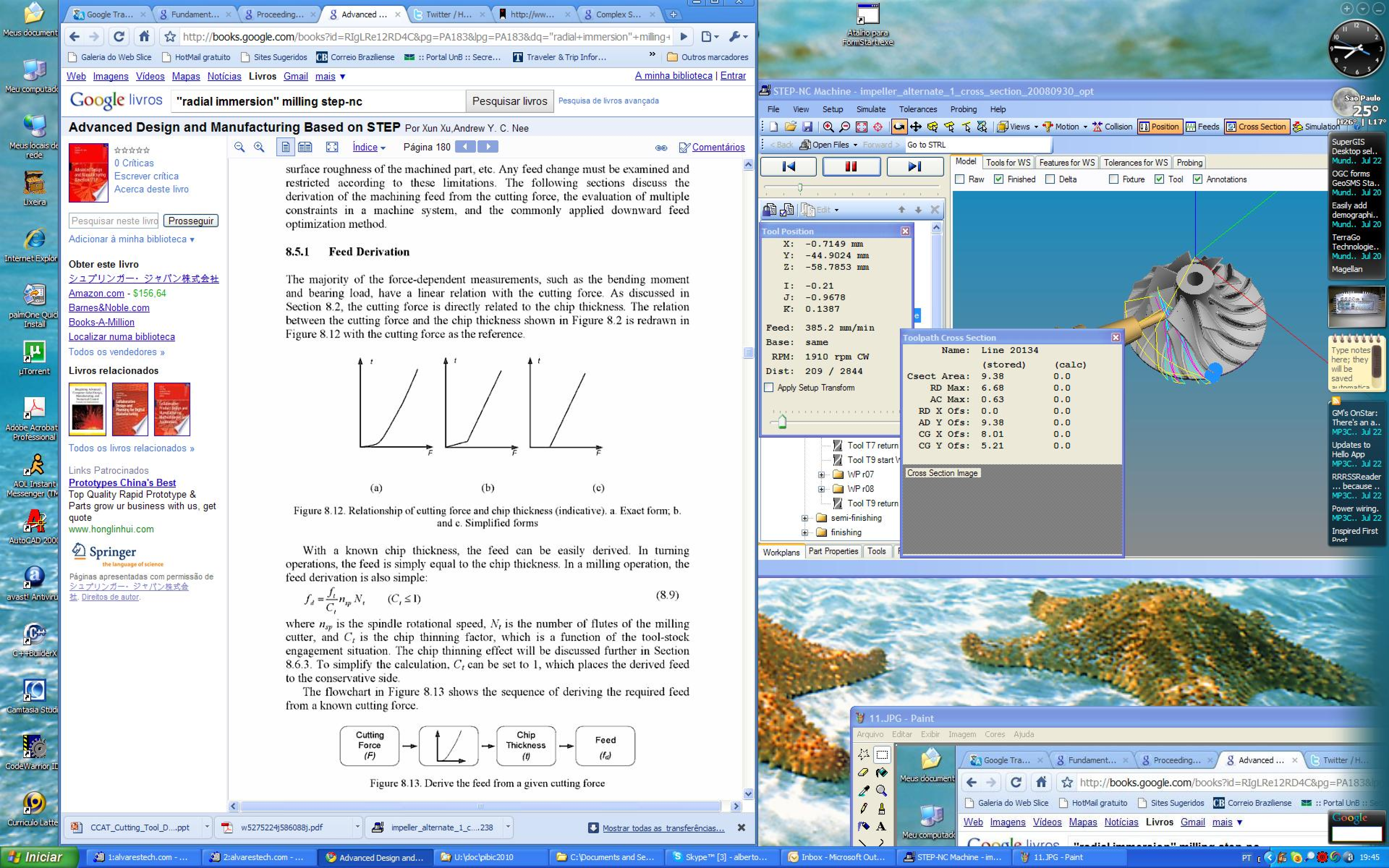
Tool Position

```
    X:  59.4748 mm
    Y:  -49.958 mm
    Z:  -105.843 mm

    I:  -0.0885
    J:  -0.3819
    K:  0.9199

 Feed:  381.61 mm/min ...
 Base:  385.2 mm/min
  RPM:  1910 rpm CW
 Dist:  37 / 2844
```

☐ Apply Setup Transform

olpath Cross Section

```
        Name:  Line 19961
               (stored)     (calc)
sect Area:     9.46         0.0
      RD Max:  7.59         0.0
      AC Max:  0.55         0.0
    RD X Ofs:  0.0          0.0
    AD Y Ofs:  9.46         0.0
    CG X Ofs:  8.11         0.0
    CG Y Ofs:  5.08         0.0
```



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surface roughness of the machined part, etc. Any feed change must be examined and restricted according to these limitations. The following sections discuss the derivation of the machining feed from the cutting force, the evaluation of multiple constraints in a machine system, and the commonly applied downward feed optimization method.

8.5.1 Feed Derivation

The majority of the force-dependent measurements, such as the bending moment and bearing load, have a linear relation with the cutting force. As discussed in Section 8.2, the cutting force is directly related to the chip thickness. The relation between the cutting force and the chip thickness shown in Figure 8.2 is redrawn in Figure 8.12 with the cutting force as the reference.

Figure 8.12. Relationship of cutting force and chip thickness (indicative). a. Exact form; b. and c. Simplified forms

With a known chip thickness, the feed can be easily derived. In turning operations, the feed is simply equal to the chip thickness. In a milling operation, the feed derivation is also simple:

$$f_d = \frac{f_t}{C_t} n_{sp} N_t \qquad (C_t \le 1) \tag{8.9}$$

where n_{sp} is the spindle rotational speed, N_t is the number of flutes of the milling cutter, and C_t is the chip thinning factor, which is a function of the tool-stock engagement situation. The chip thinning effect will be discussed further in Section 8.6.3. To simplify the calculation, C_t can be set to 1, which places the derived feed to the conservative side.

The flowchart in Figure 8.13 shows the sequence of deriving the required feed from a known cutting force.

Figure 8.13. Derive the feed from a given cutting force

Tool Position

X: -0.7149 mm
Y: -44.9024 mm
Z: -58.7853 mm

I: -0.21
J: -0.9678
K: 0.1387

Feed: 385.2 mm/min
Base: same
RPM: 1910 rpm CW
Dist: 209 / 2844

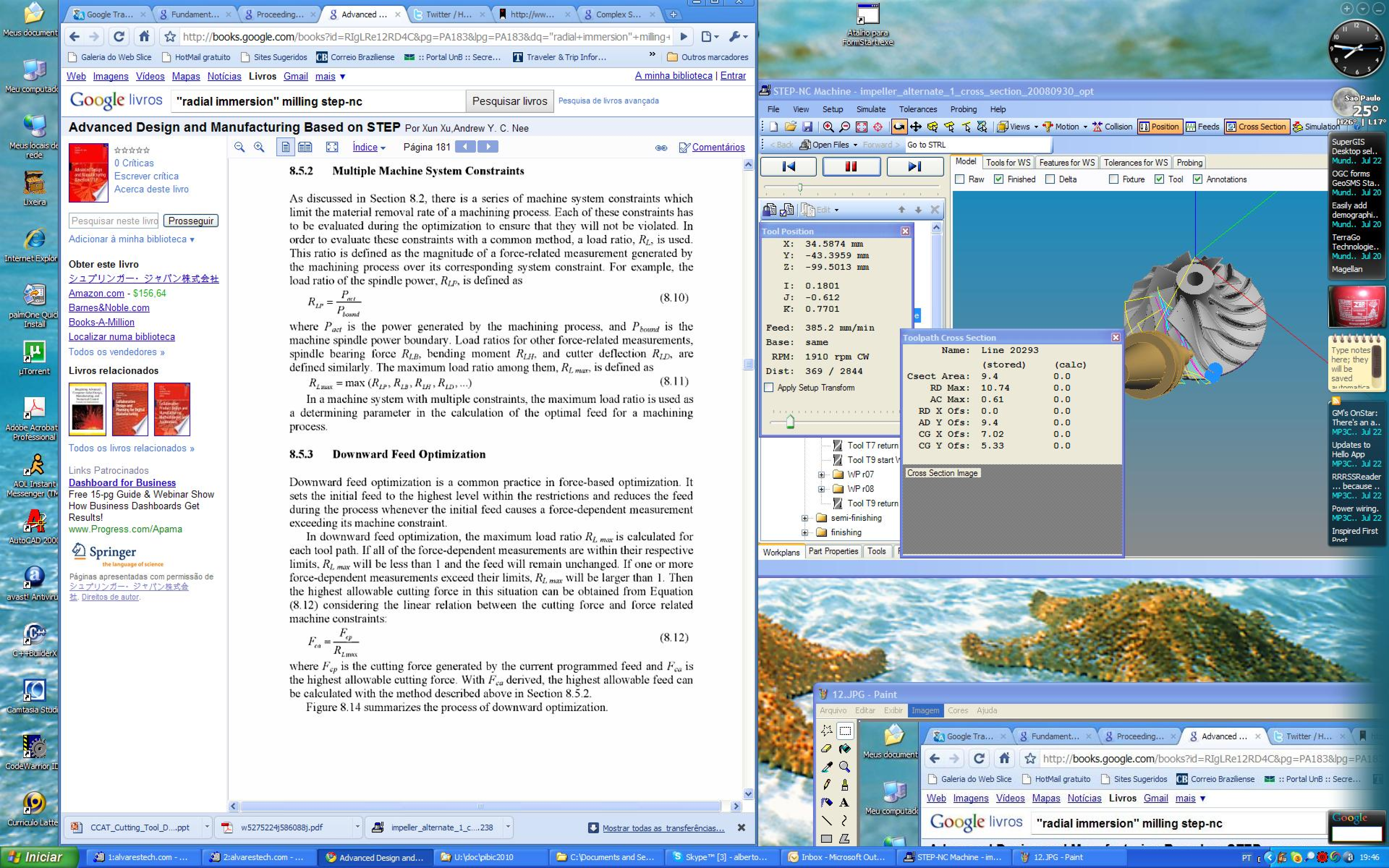
☐ Apply Setup Transform

Toolpath Cross Section

Name: Line 20134

	(stored)	(calc)
Csect Area:	9.38	0.0
RD Max:	6.68	0.0
AC Max:	0.63	0.0
RD X Ofs:	0.0	0.0
AD Y Ofs:	9.38	0.0
CG X Ofs:	8.01	0.0
CG Y Ofs:	5.21	0.0

☐ Raw ☑ Finished ☐ Delta ☐ Fixture ☑ Tool ☑ Annotations



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8.5.2 Multiple Machine System Constraints

As discussed in Section 8.2, there is a series of machine system constraints which limit the material removal rate of a machining process. Each of these constraints has to be evaluated during the optimization to ensure that they will not be violated. In order to evaluate these constraints with a common method, a load ratio, R_L, is used. This ratio is defined as the magnitude of a force-related measurement generated by the machining process over its corresponding system constraint. For example, the load ratio of the spindle power, R_{LP}, is defined as

$$R_{LP} = \frac{P_{act}}{P_{bound}} \qquad (8.10)$$

where P_{act} is the power generated by the machining process, and P_{bound} is the machine spindle power boundary. Load ratios for other force-related measurements, spindle bearing force R_{LB}, bending moment R_{LH}, and cutter deflection R_{LD}, are defined similarly. The maximum load ratio among them, $R_{L\,max}$, is defined as

$$R_{L\max} = \max(R_{LP}, R_{LB}, R_{LH}, R_{LD}, \ldots) \qquad (8.11)$$

In a machine system with multiple constraints, the maximum load ratio is used as a determining parameter in the calculation of the optimal feed for a machining process.

8.5.3 Downward Feed Optimization

Downward feed optimization is a common practice in force-based optimization. It sets the initial feed to the highest level within the restrictions and reduces the feed during the process whenever the initial feed causes a force-dependent measurement exceeding its machine constraint.

In downward feed optimization, the maximum load ratio $R_{L,\,max}$ is calculated for each tool path. If all of the force-dependent measurements are within their respective limits, $R_{L,\,max}$ will be less than 1 and the feed will remain unchanged. If one or more force-dependent measurements exceed their limits, $R_{L,\,max}$ will be larger than 1. Then the highest allowable cutting force in this situation can be obtained from Equation (8.12) considering the linear relation between the cutting force and force related machine constraints:

$$F_{ca} = \frac{F_{cp}}{R_{L\max}} \qquad (8.12)$$

where F_{cp} is the cutting force generated by the current programmed feed and F_{ca} is the highest allowable cutting force. With F_{ca} derived, the highest allowable feed can be calculated with the method described above in Section 8.5.2.

Figure 8.14 summarizes the process of downward optimization.

Tool Position

```
   X:  34.5874 mm
   Y:  -43.3959 mm
   Z:  -99.5013 mm

   I:  0.1801
   J:  -0.612
   K:  0.7701

Feed:  385.2 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  369 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
         Name:  Line 20293
                (stored)     (calc)
Csect Area:     9.4          0.0
    RD Max:     10.74        0.0
    AC Max:     0.61         0.0
  RD X Ofs:     0.0          0.0
  AD Y Ofs:     9.4          0.0
  CG X Ofs:     7.02         0.0
  CG Y Ofs:     5.33         0.0
```

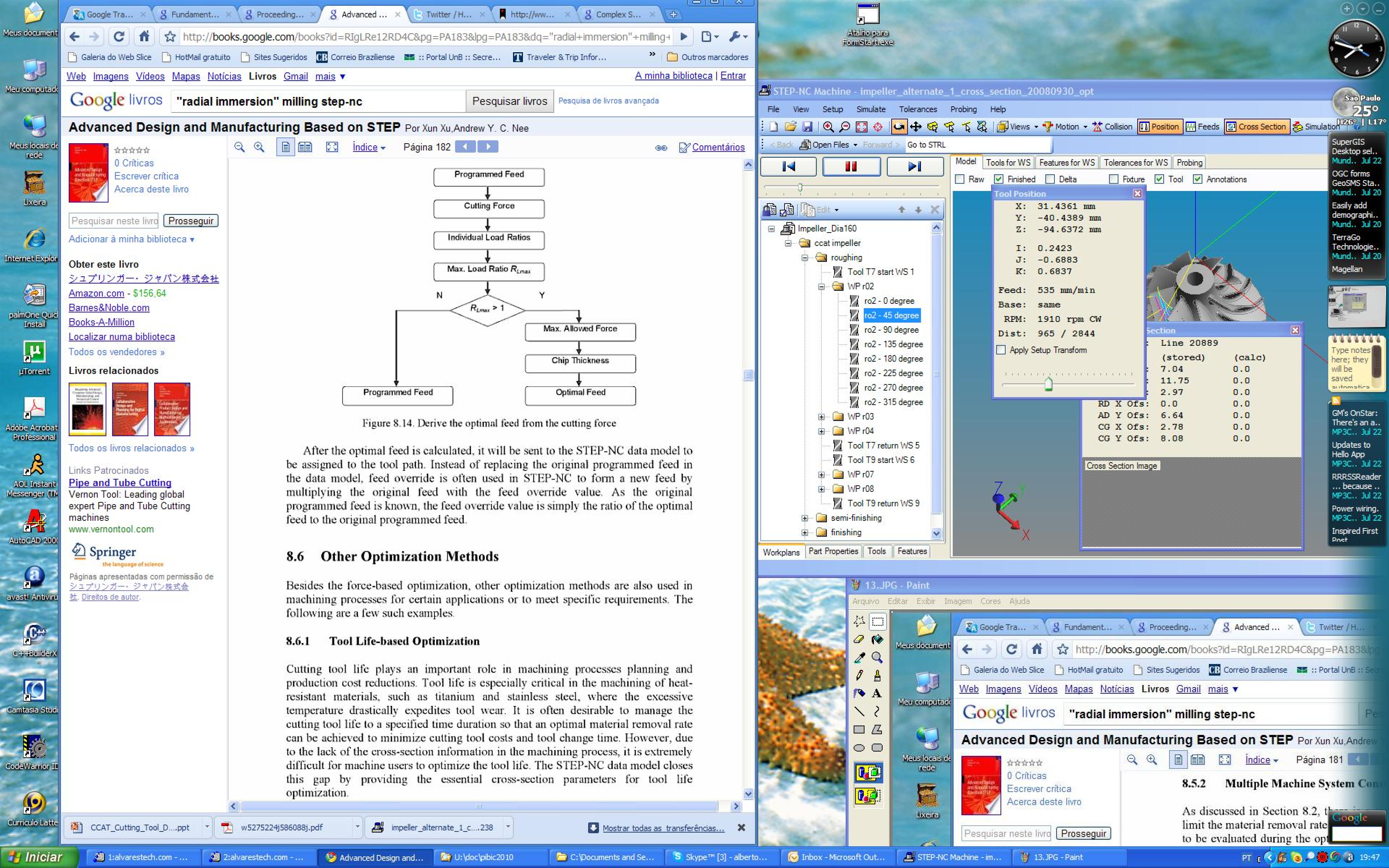

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Figure 8.14. Derive the optimal feed from the cutting force

After the optimal feed is calculated, it will be sent to the STEP-NC data model to be assigned to the tool path. Instead of replacing the original programmed feed in the data model, feed override is often used in STEP-NC to form a new feed by multiplying the original feed with the feed override value. As the original programmed feed is known, the feed override value is simply the ratio of the optimal feed to the original programmed feed.

8.6 Other Optimization Methods

Besides the force-based optimization, other optimization methods are also used in machining processes for certain applications or to meet specific requirements. The following are a few such examples.

8.6.1 Tool Life-based Optimization

Cutting tool life plays an important role in machining processes planning and production cost reductions. Tool life is especially critical in the machining of heat-resistant materials, such as titanium and stainless steel, where the excessive temperature drastically expedites tool wear. It is often desirable to manage the cutting tool life to a specified time duration so that an optimal material removal rate can be achieved to minimize cutting tool costs and tool change time. However, due to the lack of the cross-section information in the machining process, it is extremely difficult for machine users to optimize the tool life. The STEP-NC data model closes this gap by providing the essential cross-section parameters for tool life optimization.

STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

- Impeller_Dia160
  - ccat impeller
    - roughing
      - Tool T7 start WS 1
      - WP r02
        - ro2 - 0 degree
        - ro2 - 45 degree
        - ro2 - 90 degree
        - ro2 - 135 degree
        - ro2 - 180 degree
        - ro2 - 225 degree
        - ro2 - 270 degree
        - ro2 - 315 degree
      - WP r03
      - WP r04
      - Tool T7 return WS 5
      - Tool T9 start WS 6
      - WP r07
      - WP r08
      - Tool T9 return WS 9
    - semi-finishing
    - finishing

Tool Position

```
    X:  31.4361 mm
    Y:  -40.4389 mm
    Z:  -94.6372 mm

    I:  0.2423
    J:  -0.6883
    K:  0.6837

 Feed:  535 mm/min
 Base:  same
  RPM:  1910 rpm CW
 Dist:  965 / 2844
```

☐ Apply Setup Transform

Section

```
     Line 20889
     (stored)      (calc)
     7.04          0.0
     11.75         0.0
     2.97          0.0
RD X Ofs:  0.0     0.0
AD Y Ofs:  6.64    0.0
CG X Ofs:  2.78    0.0
CG Y Ofs:  8.08    0.0
```

Cross Section Image

13.JPG - Paint

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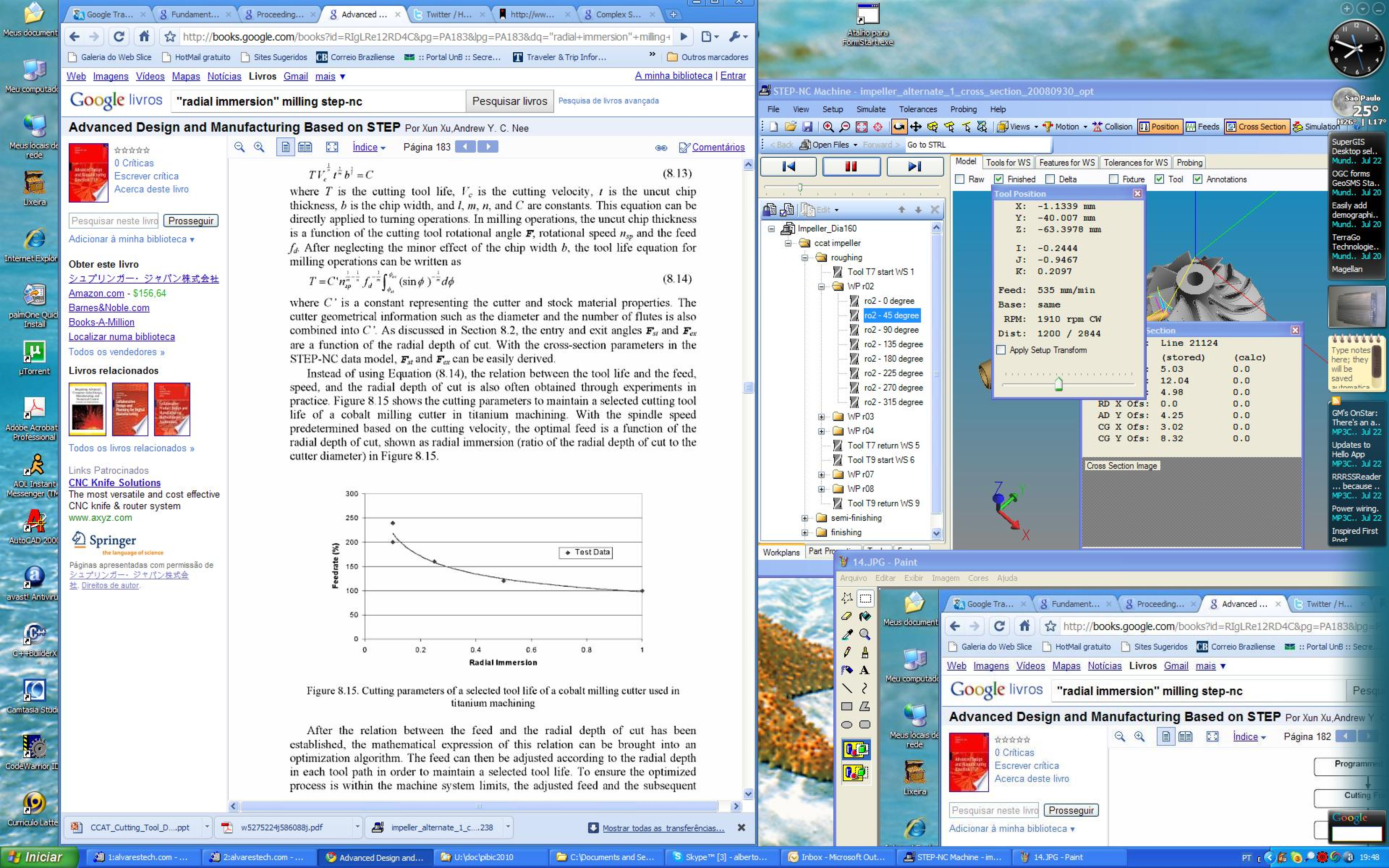
8.5.2 Multiple Machine System Con

As discussed in Section 8.2, th
limit the material removal rate
to be evaluated during the opt



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$$T V_c^{\frac{1}{n}} t^{\frac{1}{m}} b^{\frac{1}{l}} = C \qquad (8.13)$$

where T is the cutting tool life, V_c is the cutting velocity, t is the uncut chip thickness, b is the chip width, and l, m, n, and C are constants. This equation can be directly applied to turning operations. In milling operations, the uncut chip thickness is a function of the cutting tool rotational angle $\boldsymbol{F}$, rotational speed n_{sp} and the feed f_d. After neglecting the minor effect of the chip width b, the tool life equation for milling operations can be written as

$$T = C' n_{sp}^{\frac{1}{m}-\frac{1}{n}} f_d^{-\frac{1}{m}} \int_{\phi_{st}}^{\phi_{ex}} (\sin\phi)^{-\frac{1}{m}} d\phi \qquad (8.14)$$

where C' is a constant representing the cutter and stock material properties. The cutter geometrical information such as the diameter and the number of flutes is also combined into C'. As discussed in Section 8.2, the entry and exit angles $\boldsymbol{F}_{st}$ and $\boldsymbol{F}_{ex}$ are a function of the radial depth of cut. With the cross-section parameters in the STEP-NC data model, $\boldsymbol{F}_{st}$ and $\boldsymbol{F}_{ex}$ can be easily derived.

Instead of using Equation (8.14), the relation between the tool life and the feed, speed, and the radial depth of cut is also often obtained through experiments in practice. Figure 8.15 shows the cutting parameters to maintain a selected cutting tool life of a cobalt milling cutter in titanium machining. With the spindle speed predetermined based on the cutting velocity, the optimal feed is a function of the radial depth of cut, shown as radial immersion (ratio of the radial depth of cut to the cutter diameter) in Figure 8.15.

Figure 8.15. Cutting parameters of a selected tool life of a cobalt milling cutter used in titanium machining

After the relation between the feed and the radial depth of cut has been established, the mathematical expression of this relation can be brought into an optimization algorithm. The feed can then be adjusted according to the radial depth in each tool path in order to maintain a selected tool life. To ensure the optimized process is within the machine system limits, the adjusted feed and the subsequent

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Tool Position

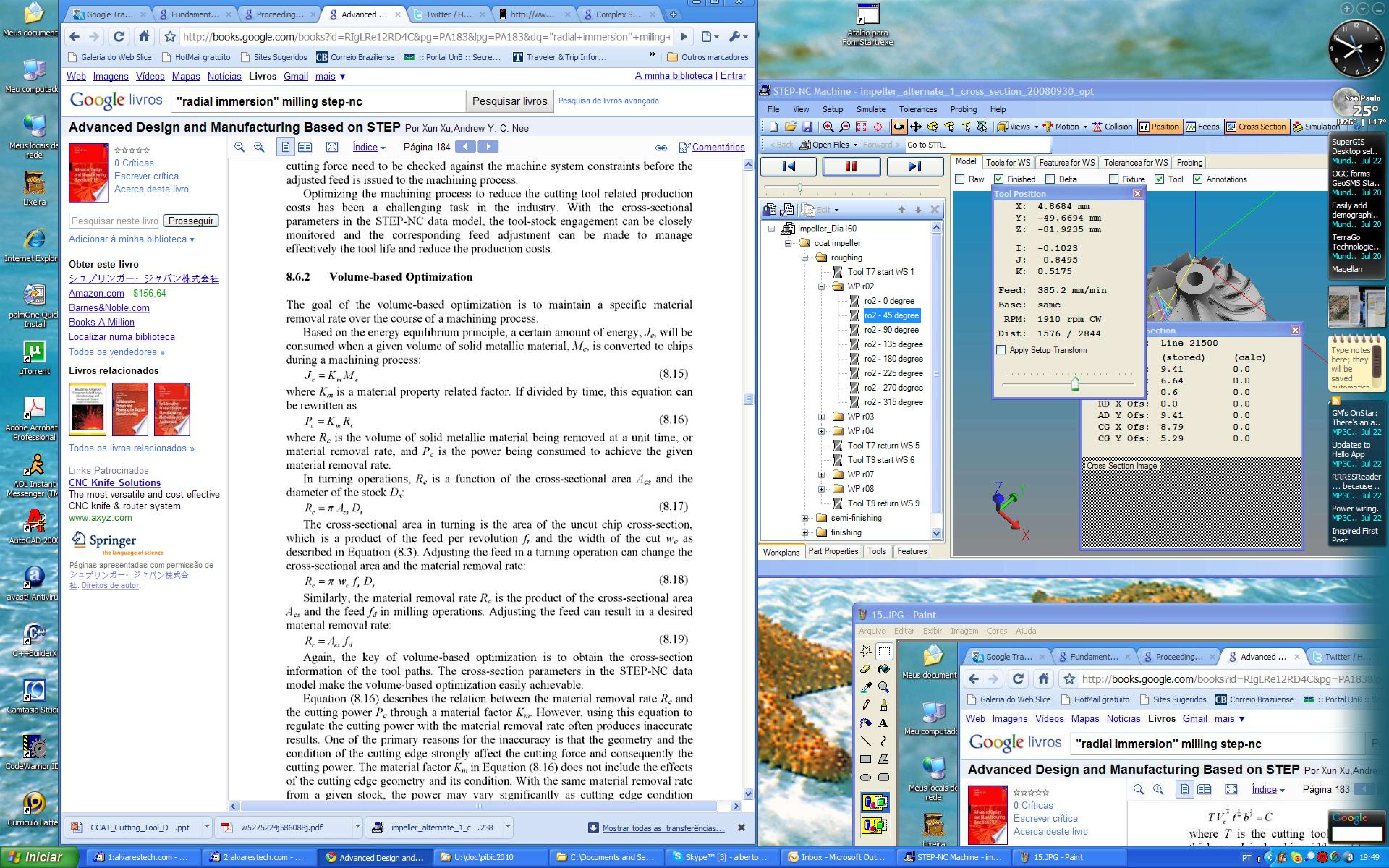
X:	-1.1339 mm
Y:	-40.007 mm
Z:	-63.3978 mm
I:	-0.2444
J:	-0.9467
K:	0.2097
Feed:	535 mm/min
Base:	same
RPM:	1910 rpm CW
Dist:	1200 / 2844

☐ Apply Setup Transform

Line 21124

	(stored)	(calc)
	5.03	0.0
	12.04	0.0
	4.98	0.0
RD X Ofs:	0.0	0.0
AD Y Ofs:	4.25	0.0
CG X Ofs:	3.02	0.0
CG Y Ofs:	8.32	0.0

Impeller_Dia160
- ccat impeller
  - roughing
    - Tool T7 start WS 1
    - WP r02
      - ro2 - 0 degree
      - ro2 - 45 degree
      - ro2 - 90 degree
      - ro2 - 135 degree
      - ro2 - 180 degree
      - ro2 - 225 degree
      - ro2 - 270 degree
      - ro2 - 315 degree
    - WP r03
    - WP r04
    - Tool T7 return WS 5
    - Tool T9 start WS 6
    - WP r07
    - WP r08
    - Tool T9 return WS 9
  - semi-finishing
  - finishing



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cutting force need to be checked against the machine system constraints before the adjusted feed is issued to the machining process.

Optimizing the machining process to reduce the cutting tool related production costs has been a challenging task in the industry. With the cross-sectional parameters in the STEP-NC data model, the tool-stock engagement can be closely monitored and the corresponding feed adjustment can be made to manage effectively the tool life and reduce the production costs.

8.6.2 Volume-based Optimization

The goal of the volume-based optimization is to maintain a specific material removal rate over the course of a machining process.

Based on the energy equilibrium principle, a certain amount of energy, J_c, will be consumed when a given volume of solid metallic material, M_c, is converted to chips during a machining process:

$$J_c = K_m M_c \tag{8.15}$$

where K_m is a material property related factor. If divided by time, this equation can be rewritten as

$$P_c = K_m R_c \tag{8.16}$$

where R_c is the volume of solid metallic material being removed at a unit time, or material removal rate, and P_c is the power being consumed to achieve the given material removal rate.

In turning operations, R_c is a function of the cross-sectional area A_{cs} and the diameter of the stock D_s:

$$R_c = \pi A_{cs} D_s \tag{8.17}$$

The cross-sectional area in turning is the area of the uncut chip cross-section, which is a product of the feed per revolution f_r and the width of the cut w_c as described in Equation (8.3). Adjusting the feed in a turning operation can change the cross-sectional area and the material removal rate:

$$R_c = \pi w_c f_r D_s \tag{8.18}$$

Similarly, the material removal rate R_c is the product of the cross-sectional area A_{cs} and the feed f_d in milling operations. Adjusting the feed can result in a desired material removal rate:

$$R_c = A_{cs} f_d \tag{8.19}$$

Again, the key of volume-based optimization is to obtain the cross-section information of the tool paths. The cross-section parameters in the STEP-NC data model make the volume-based optimization easily achievable.

Equation (8.16) describes the relation between the material removal rate R_c and the cutting power P_c through a material factor K_m. However, using this equation to regulate the cutting power with the material removal rate often produces inaccurate results. One of the primary reasons for the inaccuracy is that the geometry and the condition of the cutting edge strongly affect the cutting force and consequently the cutting power. The material factor K_m in Equation (8.16) does not include the effects of the cutting edge geometry and its condition. With the same material removal rate from a given stock, the power may vary significantly as cutting edge condition

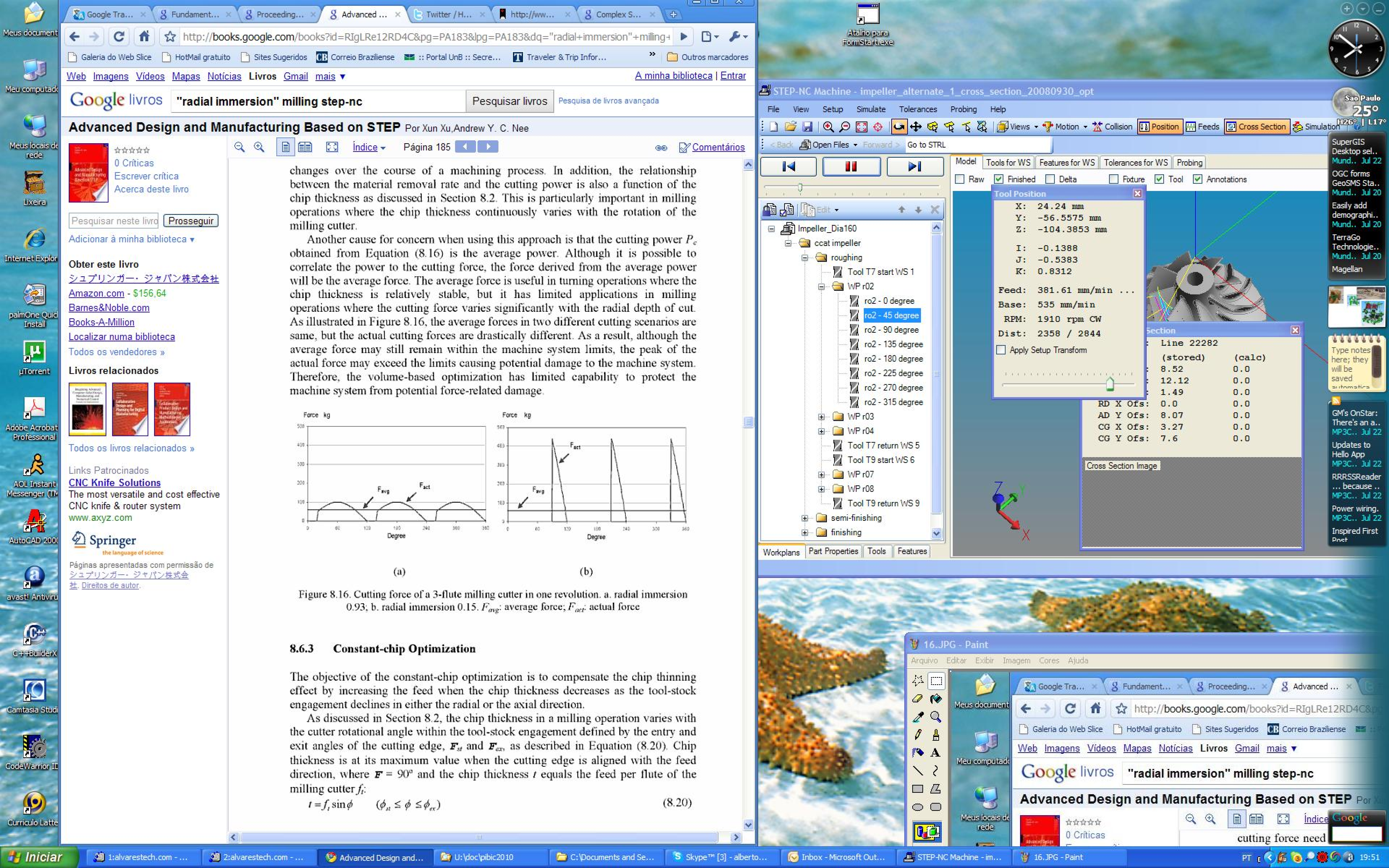
Tool Position

```
    X:  4.8684 mm
    Y:  -49.6694 mm
    Z:  -81.9235 mm

    I:  -0.1023
    J:  -0.8495
    K:  0.5175

 Feed:  385.2 mm/min
 Base:  same
  RPM:  1910 rpm CW
 Dist:  1576 / 2844
```

☐ Apply Setup Transform

Section

```
          Line 21500
          (stored)      (calc)
          9.41          0.0
          6.64          0.0
          0.6           0.0
RD X Ofs: 0.0           0.0
AD Y Ofs: 9.41          0.0
CG X Ofs: 8.79          0.0
CG Y Ofs: 5.29          0.0
```



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changes over the course of a machining process. In addition, the relationship between the material removal rate and the cutting power is also a function of the chip thickness as discussed in Section 8.2. This is particularly important in milling operations where the chip thickness continuously varies with the rotation of the milling cutter.

Another cause for concern when using this approach is that the cutting power P_c obtained from Equation (8.16) is the average power. Although it is possible to correlate the cutting power to the cutting force, the force derived from the average power will be the average force. The average force is useful in turning operations where the chip thickness is relatively stable, but it has limited applications in milling operations where the cutting force varies significantly with the radial depth of cut. As illustrated in Figure 8.16, the average forces in two different cutting scenarios are same, but the actual cutting forces are drastically different. As a result, although the average force may still remain within the machine system limits, the peak of the actual force may exceed the limits causing potential damage to the machine system. Therefore, the volume-based optimization has limited capability to protect the machine system from potential force-related damage.

Figure 8.16. Cutting force of a 3-flute milling cutter in one revolution. a. radial immersion 0.93; b. radial immersion 0.15. F_{avg}: average force; F_{act}: actual force

8.6.3 Constant-chip Optimization

The objective of the constant-chip optimization is to compensate the chip thinning effect by increasing the feed when the chip thickness decreases as the tool-stock engagement declines in either the radial or the axial direction.

As discussed in Section 8.2, the chip thickness in a milling operation varies with the cutter rotational angle within the tool-stock engagement defined by the entry and exit angles of the cutting edge, F_{st} and F_{ex}, as described in Equation (8.20). Chip thickness is at its maximum value when the cutting edge is aligned with the feed direction, where $F = 90°$ and the chip thickness t equals the feed per flute of the milling cutter f_t:

$$t = f_t \sin\phi \qquad (\phi_{st} \le \phi \le \phi_{ex}) \qquad (8.20)$$

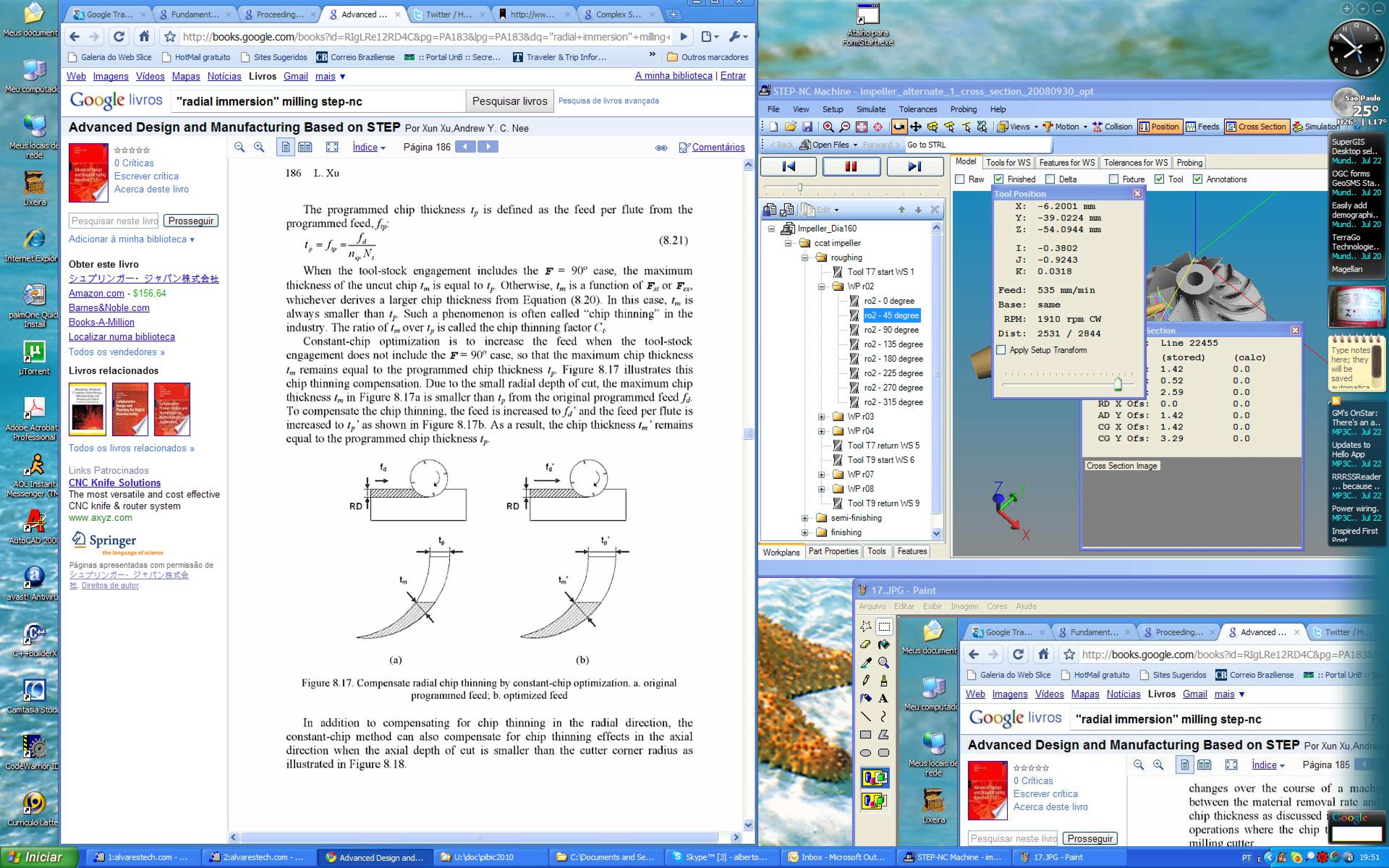
STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

```
Tool Position
  X:  24.24 mm
  Y:  -56.5575 mm
  Z:  -104.3853 mm

  I:  -0.1388
  J:  -0.5383
  K:  0.8312

Feed:  381.61 mm/min ...
Base:  535 mm/min
 RPM:  1910 rpm CW
Dist:  2358 / 2844
☐ Apply Setup Transform
```

```
Line 22282
          (stored)   (calc)
          8.52       0.0
          12.12      0.0
          1.49       0.0
RD X Ofs: 0.0        0.0
AD Y Ofs: 8.07       0.0
CG X Ofs: 3.27       0.0
CG Y Ofs: 7.6        0.0
```



☐ Raw ☑ Finished ☐ Delta ☐ Fixture ☑ Tool ☑ Annotations

```
X:  -6.2001 mm
Y:  -39.0224 mm
Z:  -54.0944 mm

I:  -0.3802
J:  -0.9243
K:  0.0318

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2531 / 2844
```

☐ Apply Setup Transform

```
           Line 22455
           (stored)      (calc)
           1.42          0.0
           0.52          0.0
           2.59          0.0
RD X Ofs:  0.0           0.0
AD Y Ofs:  1.42          0.0
CG X Ofs:  1.42          0.0
CG Y Ofs:  3.29          0.0
```

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The programmed chip thickness t_p is defined as the feed per flute from the programmed feed, f_{tp}:

$$t_p = f_{tp} = \frac{f_d}{n_{sp} N_t} \tag{8.21}$$

When the tool-stock engagement includes the $\boldsymbol{F}$ = 90° case, the maximum thickness of the uncut chip t_m is equal to t_p. Otherwise, t_m is a function of $\boldsymbol{F}_{st}$ or $\boldsymbol{F}_{ex}$, whichever derives a larger chip thickness from Equation (8.20). In this case, t_m is always smaller than t_p. Such a phenomenon is often called "chip thinning" in the industry. The ratio of t_m over t_p is called the chip thinning factor C_t.

Constant-chip optimization is to increase the feed when the tool-stock engagement does not include the $\boldsymbol{F}$ = 90° case, so that the maximum chip thickness t_m remains equal to the programmed chip thickness t_p. Figure 8.17 illustrates this chip thinning compensation. Due to the small radial depth of cut, the maximum chip thickness t_m in Figure 8.17a is smaller than t_p from the original programmed feed f_d. To compensate the chip thinning, the feed is increased to f_d' and the feed per flute is increased to t_p' as shown in Figure 8.17b. As a result, the chip thickness t_m' remains equal to the programmed chip thickness t_p.

(a) (b)

Figure 8.17. Compensate radial chip thinning by constant-chip optimization. a. original programmed feed; b. optimized feed

In addition to compensating for chip thinning in the radial direction, the constant-chip method can also compensate for chip thinning effects in the axial direction when the axial depth of cut is smaller than the cutter corner radius as illustrated in Figure 8.18.

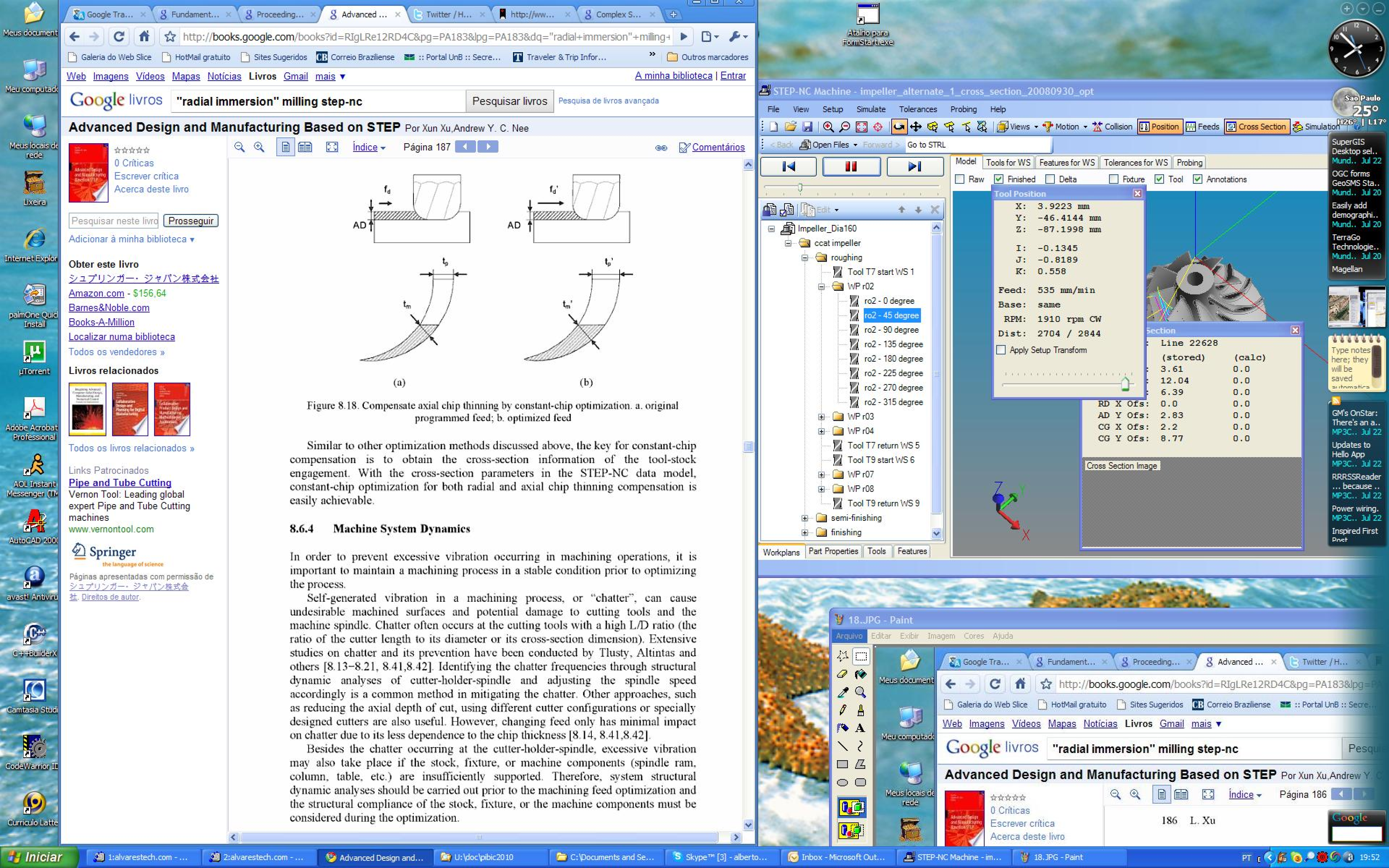

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Figure 8.18. Compensate axial chip thinning by constant-chip optimization. a. original programmed feed; b. optimized feed

Similar to other optimization methods discussed above, the key for constant-chip compensation is to obtain the cross-section information of the tool-stock engagement. With the cross-section parameters in the STEP-NC data model, constant-chip optimization for both radial and axial chip thinning compensation is easily achievable.

8.6.4 Machine System Dynamics

In order to prevent excessive vibration occurring in machining operations, it is important to maintain a machining process in a stable condition prior to optimizing the process.

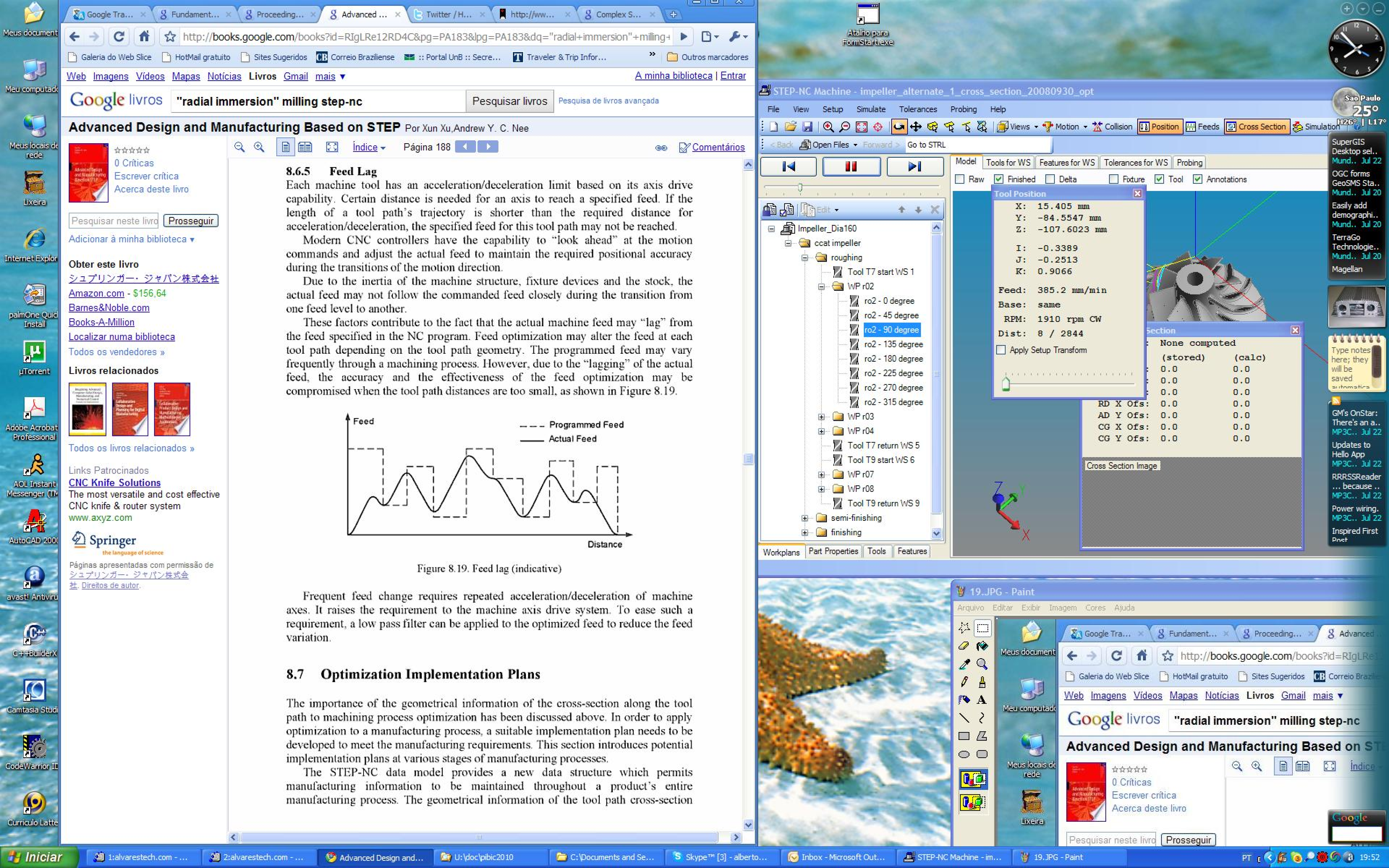
Self-generated vibration in a machining process, or "chatter", can cause undesirable machined surfaces and potential damage to cutting tools and the machine spindle. Chatter often occurs at the cutting tools with a high L/D ratio (the ratio of the cutter length to its diameter or its cross-section dimension). Extensive studies on chatter and its prevention have been conducted by Tlusty, Altintas and others [8.13–8.21, 8.41,8.42]. Identifying the chatter frequencies through structural dynamic analyses of cutter-holder-spindle and adjusting the spindle speed accordingly is a common method in mitigating the chatter. Other approaches, such as reducing the axial depth of cut, using different cutter configurations or specially designed cutters are also useful. However, changing feed only has minimal impact on chatter due to its less dependence to the chip thickness [8.14, 8.41,8.42].

Besides the chatter occurring at the cutter-holder-spindle, excessive vibration may also take place if the stock, fixture, or machine components (spindle ram, column, table, etc.) are insufficiently supported. Therefore, system structural dynamic analyses should be carried out prior to the machining feed optimization and the structural compliance of the stock, fixture, or the machine components must be considered during the optimization.

```
X:  3.9223 mm
Y:  -46.4144 mm
Z:  -87.1998 mm

I:  -0.1345
J:  -0.8189
K:  0.558

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2704 / 2844
```

☐ Apply Setup Transform

```
      Line 22628
      (stored)     (calc)
      3.61         0.0
      12.04        0.0
      6.39         0.0
RD X Ofs:  0.0     0.0
AD Y Ofs:  2.83    0.0
CG X Ofs:  2.2     0.0
CG Y Ofs:  8.77    0.0
```



8.6.5 Feed Lag

Each machine tool has an acceleration/deceleration limit based on its axis drive capability. Certain distance is needed for an axis to reach a specified feed. If the length of a tool path's trajectory is shorter than the required distance for acceleration/deceleration, the specified feed for this tool path may not be reached.

Modern CNC controllers have the capability to "look ahead" at the motion commands and adjust the actual feed to maintain the required positional accuracy during the transitions of the motion direction.

Due to the inertia of the machine structure, fixture devices and the stock, the actual feed may not follow the commanded feed closely during the transition from one feed level to another.

These factors contribute to the fact that the actual machine feed may "lag" from the feed specified in the NC program. Feed optimization may alter the feed at each tool path depending on the tool path geometry. The programmed feed may vary frequently through a machining process. However, due to the "lagging" of the machine feed, the accuracy and the effectiveness of the feed optimization may be compromised when the tool path distances are too small, as shown in Figure 8.19.

Figure 8.19. Feed lag (indicative)

Frequent feed change requires repeated acceleration/deceleration of machine axes. It raises the requirement to the machine axis drive system. To ease such a requirement, a low pass filter can be applied to the optimized feed to reduce the feed variation.

8.7 Optimization Implementation Plans

The importance of the geometrical information of the cross-section along the tool path to machining process optimization has been discussed above. In order to apply optimization to a manufacturing process, a suitable implementation plan needs to be developed to meet the manufacturing requirements. This section introduces potential implementation plans at various stages of manufacturing processes.

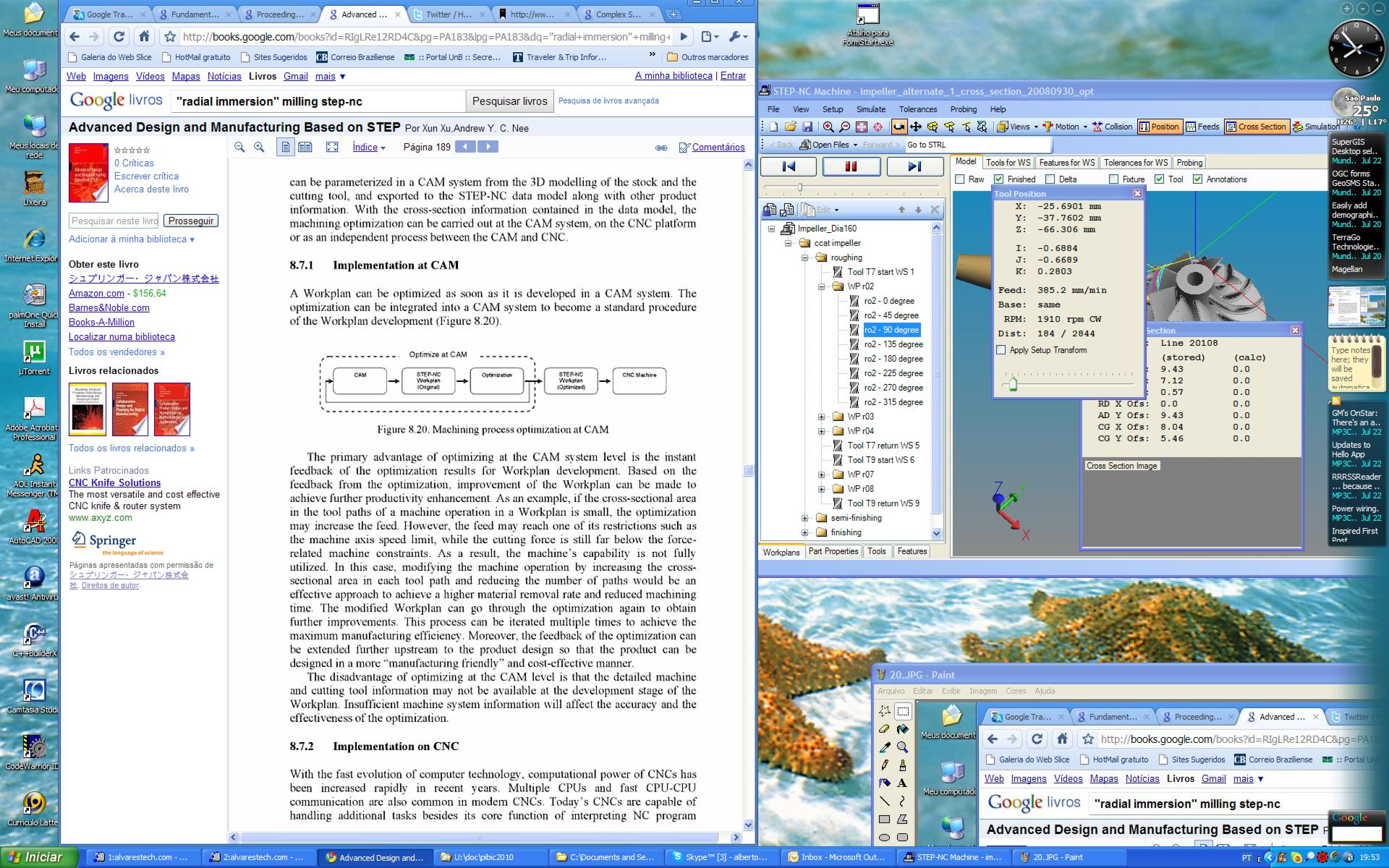
The STEP-NC data model provides a new data structure which permits manufacturing information to be maintained throughout a product's entire manufacturing process. The geometrical information of the tool path cross-section

Tool Position

```
X:  15.405 mm
Y:  -84.5547 mm
Z:  -107.6023 mm

I:  -0.3389
J:  -0.2513
K:  0.9066

Feed:  385.2 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  8 / 2844
```

☐ Apply Setup Transform

```
None computed
(stored)      (calc)
0.0           0.0
0.0           0.0
0.0           0.0
RD X Ofs:  0.0    0.0
AD Y Ofs:  0.0    0.0
CG X Ofs:  0.0    0.0
CG Y Ofs:  0.0    0.0
```



can be parameterized in a CAM system from the 3D modelling of the stock and the cutting tool, and exported to the STEP-NC data model along with other product information. With the cross-section information contained in the data model, the machining optimization can be carried out at the CAM system, on the CNC platform or as an independent process between the CAM and CNC.

8.7.1 Implementation at CAM

A Workplan can be optimized as soon as it is developed in a CAM system. The optimization can be integrated into a CAM system to become a standard procedure of the Workplan development (Figure 8.20).

Figure 8.20. Machining process optimization at CAM

The primary advantage of optimizing at the CAM system level is the instant feedback of the optimization results for Workplan development. Based on the feedback from the optimization, improvement of the Workplan can be made to achieve further productivity enhancement. As an example, if the cross-sectional area in the tool paths of a machine operation in a Workplan is small, the optimization may increase the feed. However, the feed may reach one of its restrictions such as the machine axis speed limit, while the cutting force is still far below the force-related machine constraints. As a result, the machine's capability is not fully utilized. In this case, modifying the machine operation by increasing the cross-sectional area in each tool path and reducing the number of paths would be an effective approach to achieve a higher material removal rate and reduced machining time. The modified Workplan can go through the optimization again to obtain further improvements. This process can be iterated multiple times to achieve the maximum manufacturing efficiency. Moreover, the feedback of the optimization can be extended further upstream to the product design so that the product can be designed in a more "manufacturing friendly" and cost-effective manner.

The disadvantage of optimizing at the CAM level is that the detailed machine and cutting tool information may not be available at the development stage of the Workplan. Insufficient machine system information will affect the accuracy and the effectiveness of the optimization.

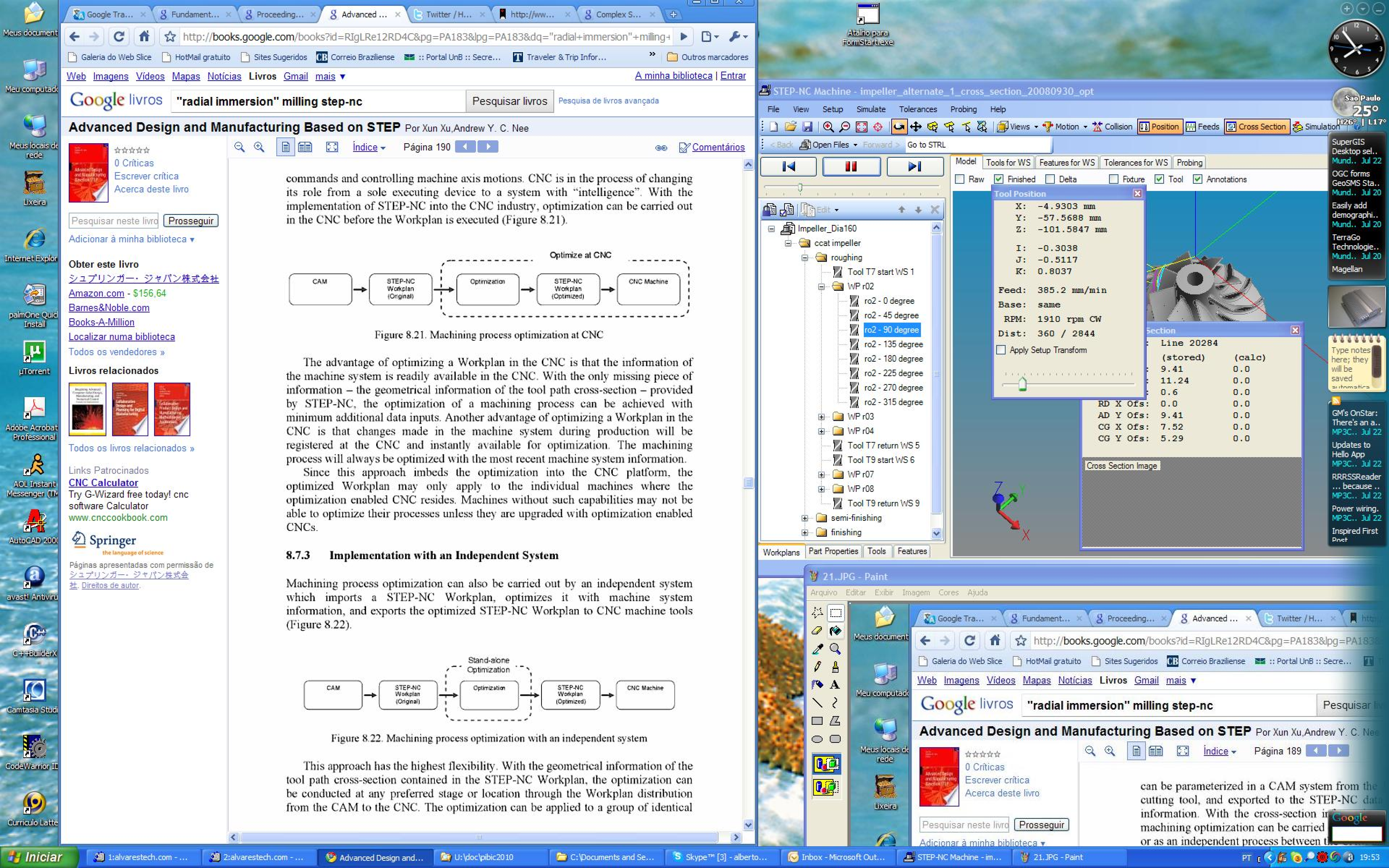
8.7.2 Implementation on CNC

With the fast evolution of computer technology, computational power of CNCs has been increased rapidly in recent years. Multiple CPUs and fast CPU-CPU communication are also common in modern CNCs. Today's CNCs are capable of handling additional tasks besides its core function of interpreting NC program

```
Tool Position
    X:  -25.6901 mm
    Y:  -37.7602 mm
    Z:  -66.306 mm

    I:  -0.6884
    J:  -0.6689
    K:  0.2803

Feed:  385.2 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  184 / 2844
```

☐ Apply Setup Transform

```
Section
          :  Line 20108
             (stored)      (calc)
          :  9.43          0.0
          :  7.12          0.0
          :  0.57          0.0
RD X Ofs:    0.0           0.0
AD Y Ofs:    9.43          0.0
CG X Ofs:    8.04          0.0
CG Y Ofs:    5.46          0.0
```



commands and controlling machine axis motions. CNC is in the process of changing its role from a sole executing device to a system with "intelligence". With the implementation of STEP-NC into the CNC industry, optimization can be carried out in the CNC before the Workplan is executed (Figure 8.21).

Figure 8.21. Machining process optimization at CNC

The advantage of optimizing a Workplan in the CNC is that the information of the machine system is readily available in the CNC. With the only missing piece of information – the geometrical information of the tool path cross-section – provided by STEP-NC, the optimization of a machining process can be achieved with minimum additional data inputs. Another advantage of optimizing a Workplan in the CNC is that changes made in the machine system during production will be registered at the CNC and instantly available for optimization. The machining process will always be optimized with the most recent machine system information.

Since this approach imbeds the optimization into the CNC platform, the optimized Workplan may only apply to the individual machines where the optimization enabled CNC resides. Machines without such capabilities may not be able to optimize their processes unless they are upgraded with optimization enabled CNCs.

8.7.3 Implementation with an Independent System

Machining process optimization can also be carried out by an independent system which imports a STEP-NC Workplan, optimizes it with machine system information, and exports the optimized STEP-NC Workplan to CNC machine tools (Figure 8.22).

Figure 8.22. Machining process optimization with an independent system

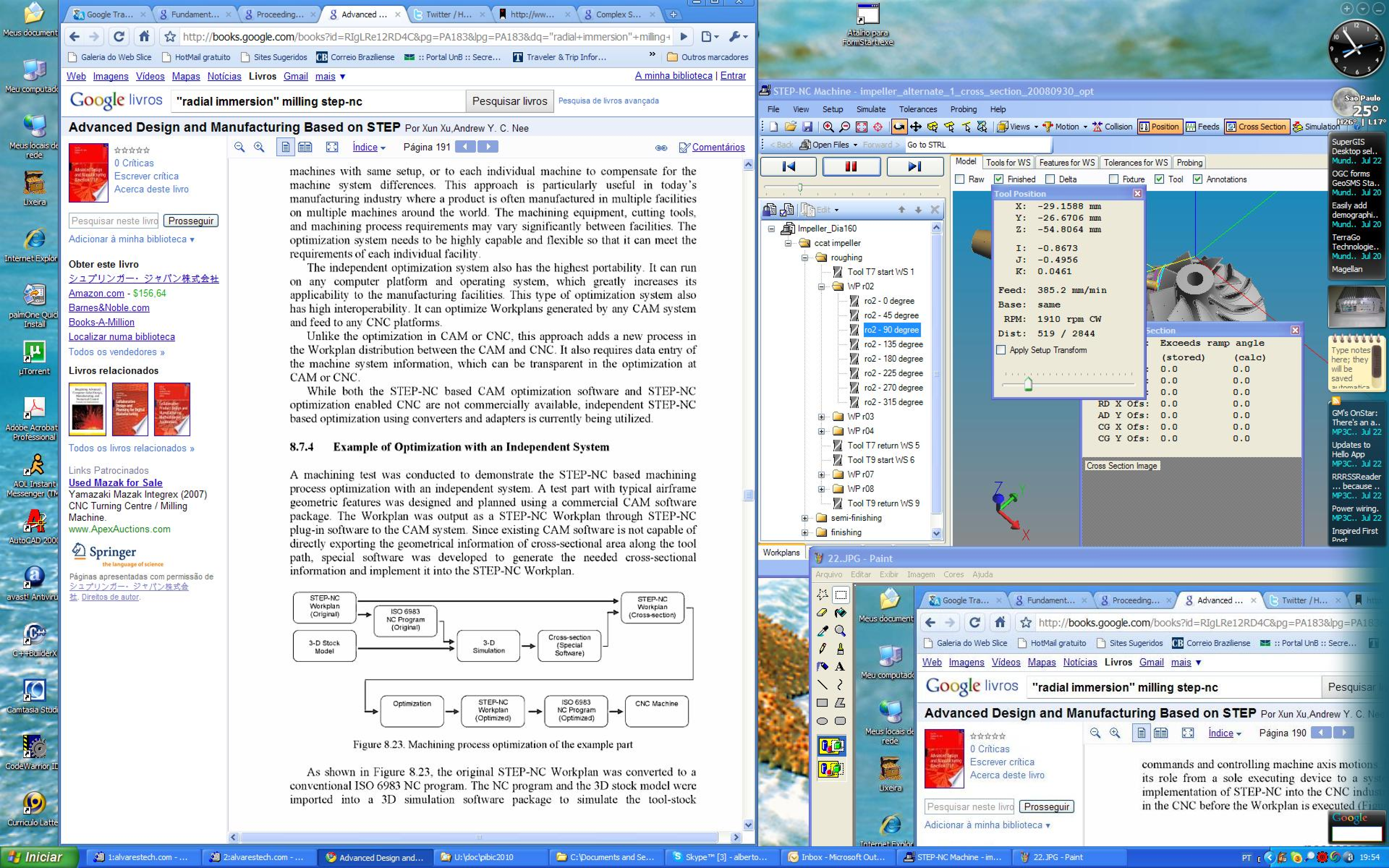
This approach has the highest flexibility. With the geometrical information of the tool path cross-section contained in the STEP-NC Workplan, the optimization can be conducted at any preferred stage or location through the Workplan distribution from the CAM to the CNC. The optimization can be applied to a group of identical

```
X:  -4.9303 mm
Y:  -57.5688 mm
Z:  -101.5847 mm

I:  -0.3038
J:  -0.5117
K:  0.8037

Feed:  385.2 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  360 / 2844
```

☐ Apply Setup Transform

```
Line 20284
       (stored)    (calc)
       9.41        0.0
       11.24       0.0
       0.6         0.0
RD X Ofs:  0.0     0.0
AD Y Ofs:  9.41    0.0
CG X Ofs:  7.52    0.0
CG Y Ofs:  5.29    0.0
```

can be parameterized in a CAM system from the cutting tool, and exported to the STEP-NC data information. With the cross-section in machining optimization can be carried or as an independent process between



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machines with same setup, or to each individual machine to compensate for the machine system differences. This approach is particularly useful in today's manufacturing industry where a product is often manufactured in multiple facilities on multiple machines around the world. The machining equipment, cutting tools, and machining process requirements may vary significantly between facilities. The optimization system needs to be highly capable and flexible so that it can meet the requirements of each individual facility.

The independent optimization system also has the highest portability. It can run on any computer platform and operating system, which greatly increases its applicability to the manufacturing facilities. This type of optimization system also has high interoperability. It can optimize Workplans generated by any CAM system and feed to any CNC platforms.

Unlike the optimization in CAM or CNC, this approach adds a new process in the Workplan distribution between the CAM and CNC. It also requires data entry of the machine system information, which can be transparent in the optimization at CAM or CNC.

While both the STEP-NC based CAM optimization software and STEP-NC optimization enabled CNC are not commercially available, independent STEP-NC based optimization using converters and adapters is currently being utilized.

8.7.4 Example of Optimization with an Independent System

A machining test was conducted to demonstrate the STEP-NC based machining process optimization with an independent system. A test part with typical airframe geometric features was designed and planned using a commercial CAM software package. The Workplan was output as a STEP-NC Workplan through STEP-NC plug-in software to the CAM system. Since existing CAM software is not capable of directly exporting the geometrical information of cross-sectional area along the tool path, special software was developed to generate the needed cross-sectional information and implement it into the STEP-NC Workplan.

Figure 8.23. Machining process optimization of the example part

As shown in Figure 8.23, the original STEP-NC Workplan was converted to a conventional ISO 6983 NC program. The NC program and the 3D stock model were imported into a 3D simulation software package to simulate the tool-stock

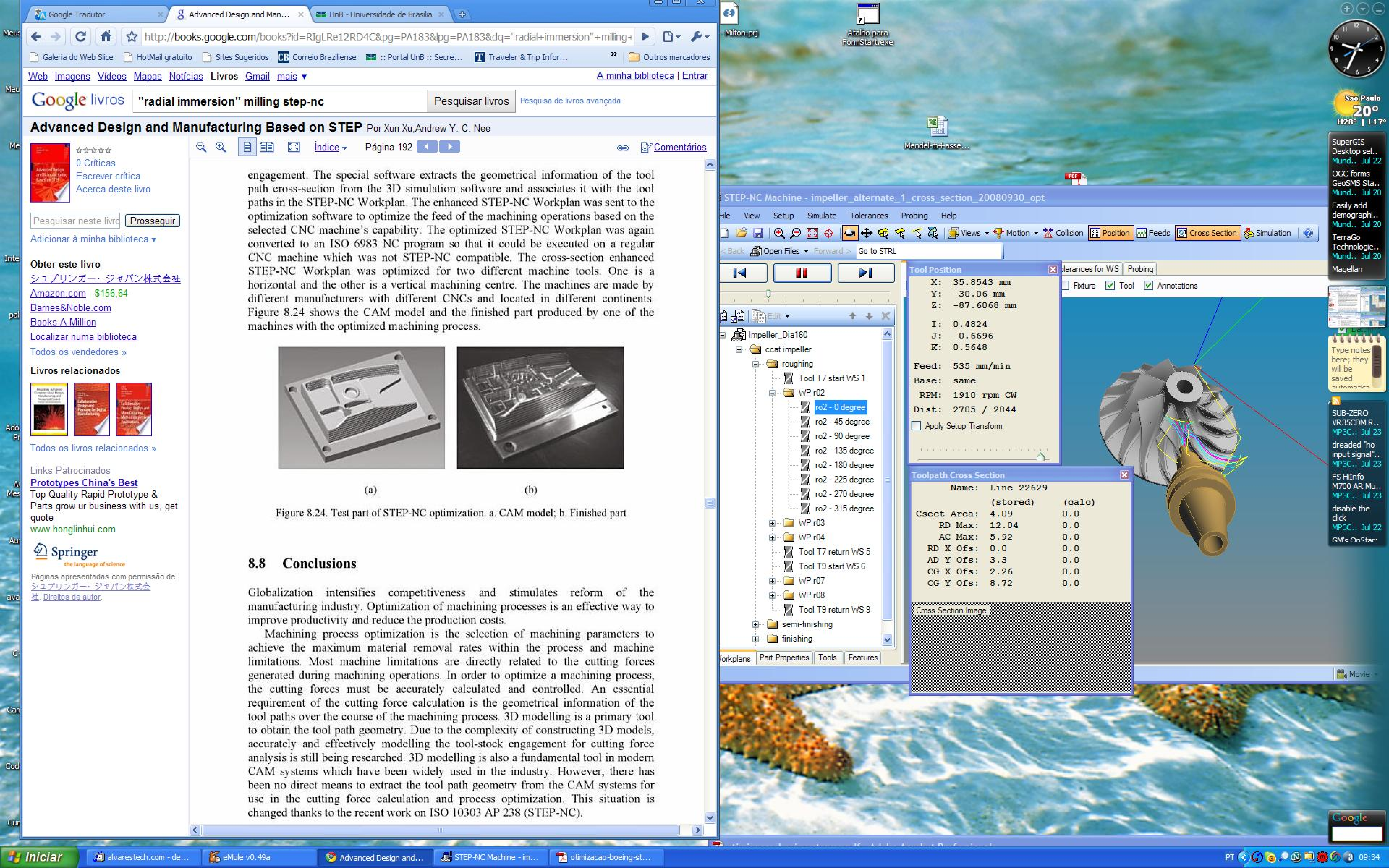
Tool Position

X: -29.1588 mm
Y: -26.6706 mm
Z: -54.8064 mm
I: -0.8673
J: -0.4956
K: 0.0461
Feed: 385.2 mm/min
Base: same
RPM: 1910 rpm CW
Dist: 519 / 2844
☐ Apply Setup Transform

Cross Section

	Exceeds ramp angle (stored)	(calc)
	0.0	0.0
	0.0	0.0
	0.0	0.0
RD X Ofs:	0.0	0.0
AD Y Ofs:	0.0	0.0
CG X Ofs:	0.0	0.0
CG Y Ofs:	0.0	0.0

commands and controlling machine axis motions its role from a sole executing device to a syst implementation of STEP-NC into the CNC indust in the CNC before the Workplan is executed (Fig



engagement. The special software extracts the geometrical information of the tool path cross-section from the 3D simulation software and associates it with the tool paths in the STEP-NC Workplan. The enhanced STEP-NC Workplan was sent to the optimization software to optimize the feed of the machining operations based on the selected CNC machine's capability. The optimized STEP-NC Workplan was again converted to an ISO 6983 NC program so that it could be executed on a regular CNC machine which was not STEP-NC compatible. The cross-section enhanced STEP-NC Workplan was optimized for two different machine tools. One is a horizontal and the other is a vertical machining centre. The machines are made by different machine tool builders with different CNCs and located in different continents. Figure 8.24 shows the CAM model and the finished part produced by one of the machines with the optimized machining process.

(a) (b)

Figure 8.24. Test part of STEP-NC optimization. a. CAM model; b. Finished part

8.8 Conclusions

Globalization intensifies competitiveness and stimulates reform of the manufacturing industry. Optimization of machining processes is an effective way to improve productivity and reduce the production costs.

Machining process optimization is the selection of machining parameters to achieve the maximum material removal rates within the process and machine limitations. Most machine limitations are directly related to the cutting forces generated during machining operations. In order to optimize a machining process, the cutting forces must be accurately calculated and controlled. An essential requirement of the cutting force calculation is the geometrical information of the tool paths over the course of the machining process. 3D modelling is a primary tool to obtain the tool path geometry. Due to the complexity of constructing 3D models, accurately and effectively modelling the tool-stock engagement for cutting force analysis is still being researched. 3D modelling is also a fundamental tool in modern CAM systems which have been widely used in the industry. However, there has been no direct means to extract the tool path geometry from the CAM systems for use in the cutting force calculation and process optimization. This situation is changed thanks to the recent work on ISO 10303 AP 238 (STEP-NC).

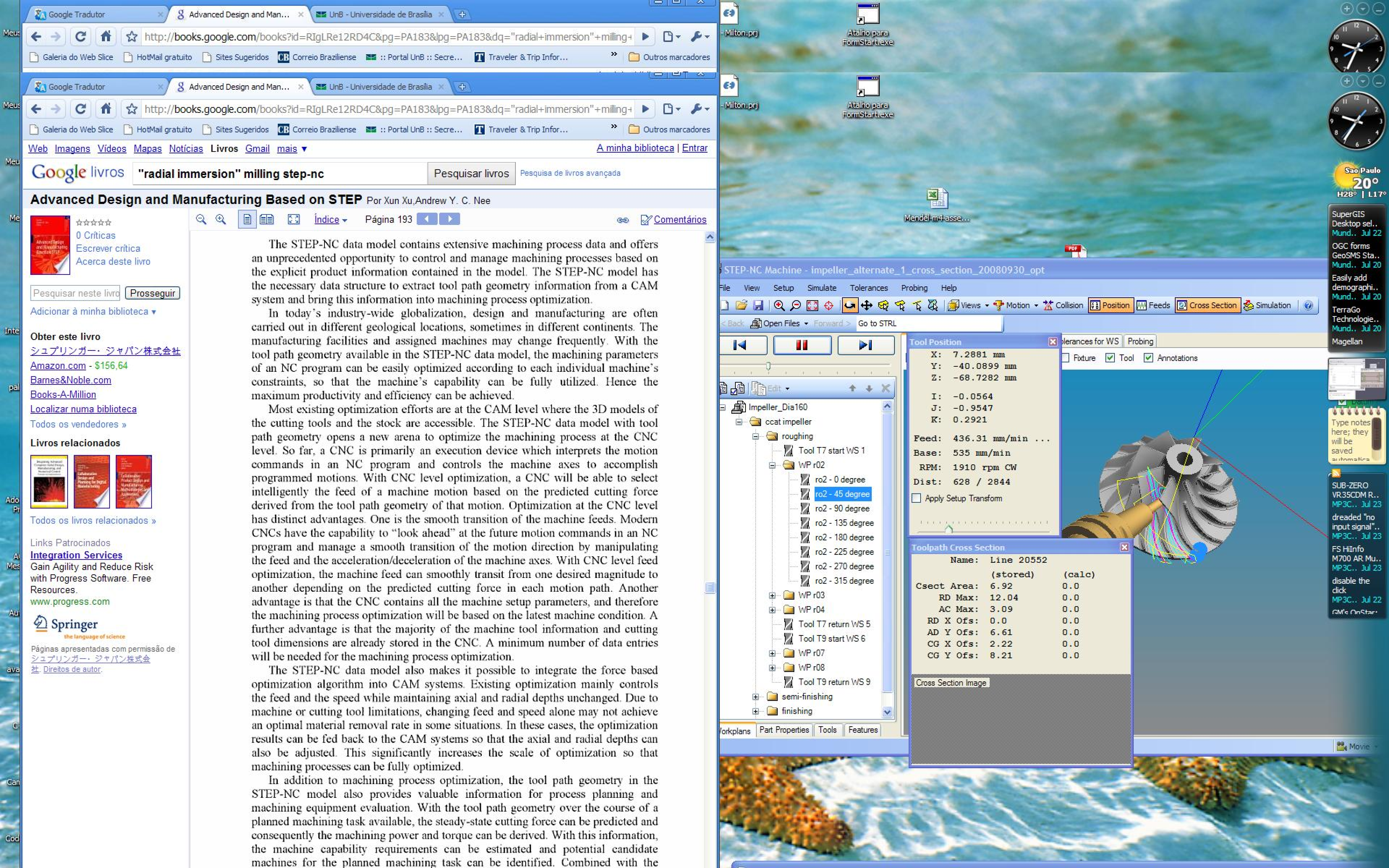
```
   X:  35.8543 mm
   Y:  -30.06 mm
   Z:  -87.6068 mm

   I:  0.4824
   J:  -0.6696
   K:  0.5648

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2705 / 2844
```

☐ Apply Setup Transform

```
       Name:  Line 22629
              (stored)    (calc)
Csect Area:   4.09        0.0
    RD Max:   12.04       0.0
    AC Max:   5.92        0.0
  RD X Ofs:   0.0         0.0
  AD Y Ofs:   3.3         0.0
  CG X Ofs:   2.26        0.0
  CG Y Ofs:   8.72        0.0
```



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The STEP-NC data model contains extensive machining process data and offers an unprecedented opportunity to control and manage machining processes based on the explicit product information contained in the model. The STEP-NC model has the necessary data structure to extract tool path geometry information from a CAM system and bring this information into machining process optimization.

In today's industry-wide globalization, design and manufacturing are often carried out in different geological locations, sometimes in different continents. The manufacturing facilities and assigned machines may change frequently. With the tool path geometry available in the STEP-NC data model, the machining parameters of an NC program can be easily optimized according to each individual machine's constraints, so that the machine's capability can be fully utilized. Hence the maximum productivity and efficiency can be achieved.

Most existing optimization efforts are at the CAM level where the 3D models of the cutting tools and the stock are accessible. The STEP-NC data model with tool path geometry opens a new arena to optimize the machining process at the CNC level. So far, a CNC is primarily an execution device which interprets the motion commands in an NC program and controls the machine axes to accomplish programmed motions. With CNC level optimization, a CNC will be able to select intelligently the feed of a machine motion based on the predicted cutting force derived from the tool path geometry of that motion. Optimization at the CNC level has distinct advantages. One is the smooth transition of the machine feeds. Modern CNCs have the capability to "look ahead" at the future motion commands in an NC program and manage a smooth transition of the motion direction by manipulating the feed and the acceleration/deceleration of the machine axes. With CNC level feed optimization, the machine feed can smoothly transit from one desired magnitude to another depending on the predicted cutting force in each motion path. Another advantage is that the CNC contains all the machine setup parameters, and therefore the machining process optimization will be based on the latest machine condition. A further advantage is that the majority of the machine tool information and cutting tool dimensions are already stored in the CNC. A minimum number of data entries will be needed for the machining process optimization.

The STEP-NC data model also makes it possible to integrate the force based optimization algorithm into CAM systems. Existing optimization mainly controls the feed and the speed while maintaining axial and radial depths unchanged. Due to machine or cutting tool limitations, changing feed and speed alone may not achieve an optimal material removal rate in some situations. In these cases, the optimization results can be fed back to the CAM systems so that the axial and radial depths can also be adjusted. This significantly increases the scale of optimization so that machining processes can be fully optimized.

In addition to machining process optimization, the tool path geometry in the STEP-NC model also provides valuable information for process planning and machining equipment evaluation. With the tool path geometry over the course of a planned machining task available, the steady-state cutting force can be predicted and consequently the machining power and torque can be derived. With this information, the machine capability requirements can be estimated and potential candidate machines for the planned machining task can be identified. Combined with the

STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

Tool Position

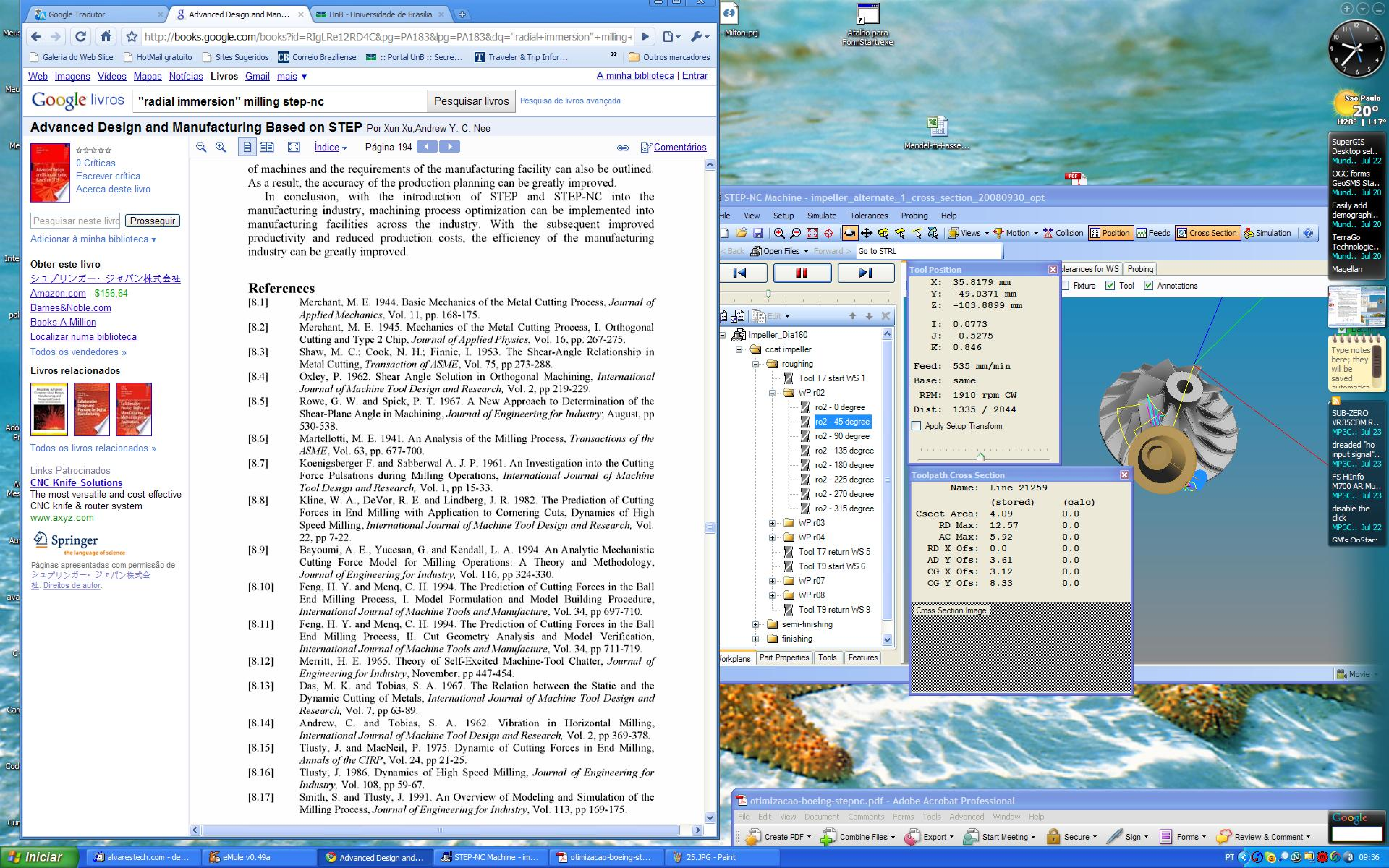
```
X:  7.2881 mm
Y:  -40.0899 mm
Z:  -68.7282 mm

I:  -0.0564
J:  -0.9547
K:  0.2921

Feed:  436.31 mm/min ...
Base:  535 mm/min
RPM:  1910 rpm CW
Dist:  628 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
      Name:  Line 20552
             (stored)     (calc)
Csect Area:  6.92         0.0
    RD Max:  12.04        0.0
    AC Max:  3.09         0.0
  RD X Ofs:  0.0          0.0
  AD Y Ofs:  6.61         0.0
  CG X Ofs:  2.22         0.0
  CG Y Ofs:  8.21         0.0
```

Cross Section Image



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of machines and the requirements of the manufacturing facility can also be outlined. As a result, the accuracy of the production planning can be greatly improved.

In conclusion, with the introduction of STEP and STEP-NC into the manufacturing industry, machining process optimization can be implemented into manufacturing facilities across the industry. With the subsequent improved productivity and reduced production costs, the efficiency of the manufacturing industry can be greatly improved.

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STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

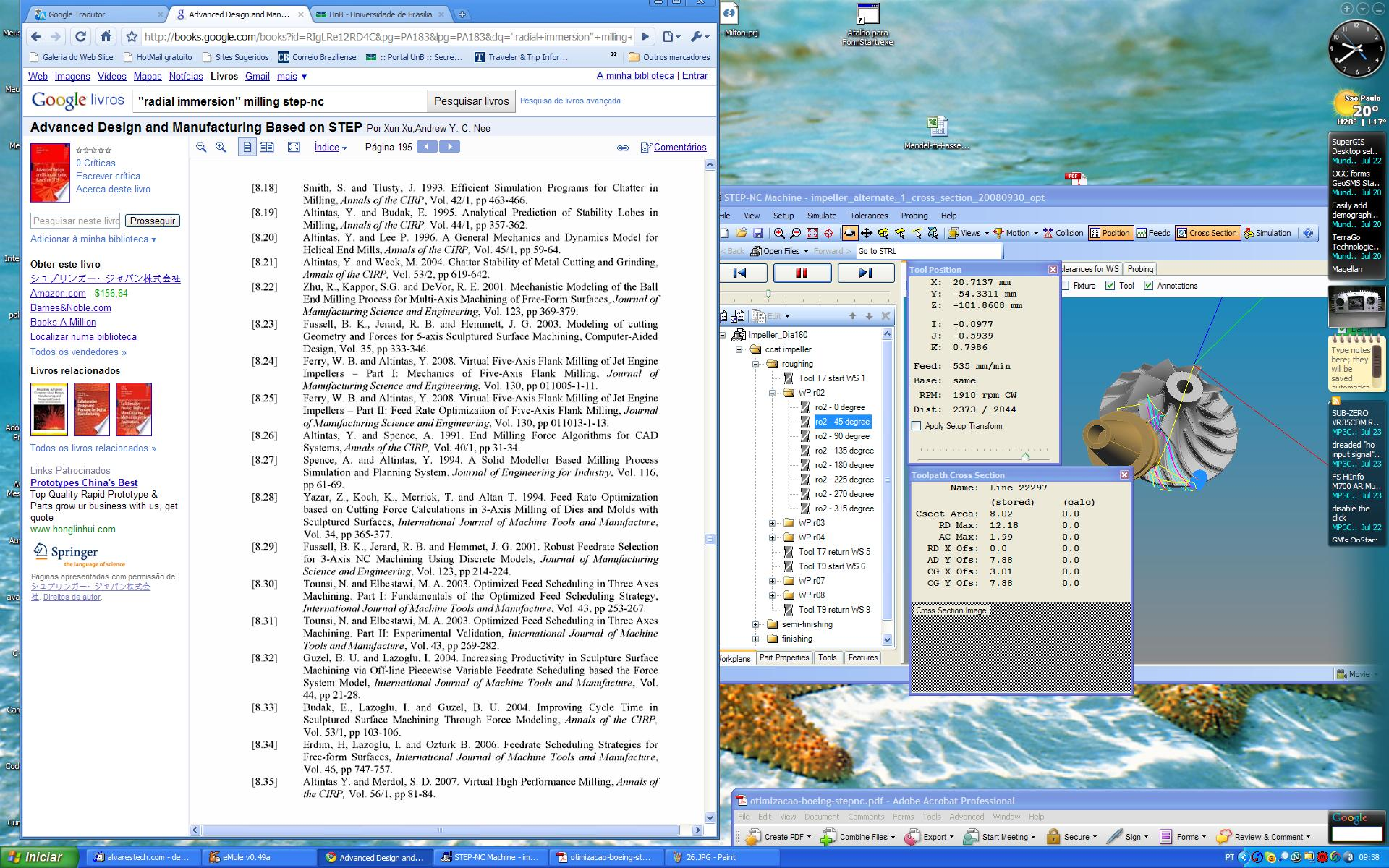
Tool Position

```
X:  35.8179 mm
Y:  -49.0371 mm
Z:  -103.8899 mm

I:  0.0773
J:  -0.5275
K:  0.846

Feed:  535 mm/min
Base:  same
RPM:   1910 rpm CW
Dist:  1335 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
        Name:  Line 21259
               (stored)     (calc)
 Csect Area:  4.09          0.0
     RD Max:  12.57         0.0
     AC Max:  5.92          0.0
   RD X Ofs:  0.0           0.0
   AD Y Ofs:  3.61          0.0
   CG X Ofs:  3.12          0.0
   CG Y Ofs:  8.33          0.0
```



http://books.google.com/books?id=RIgLRe12RD4C&pg=PA183&lpg=PA183&dq="radial+immersion"+milling+

"radial immersion" milling step-nc

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STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

Tool Position

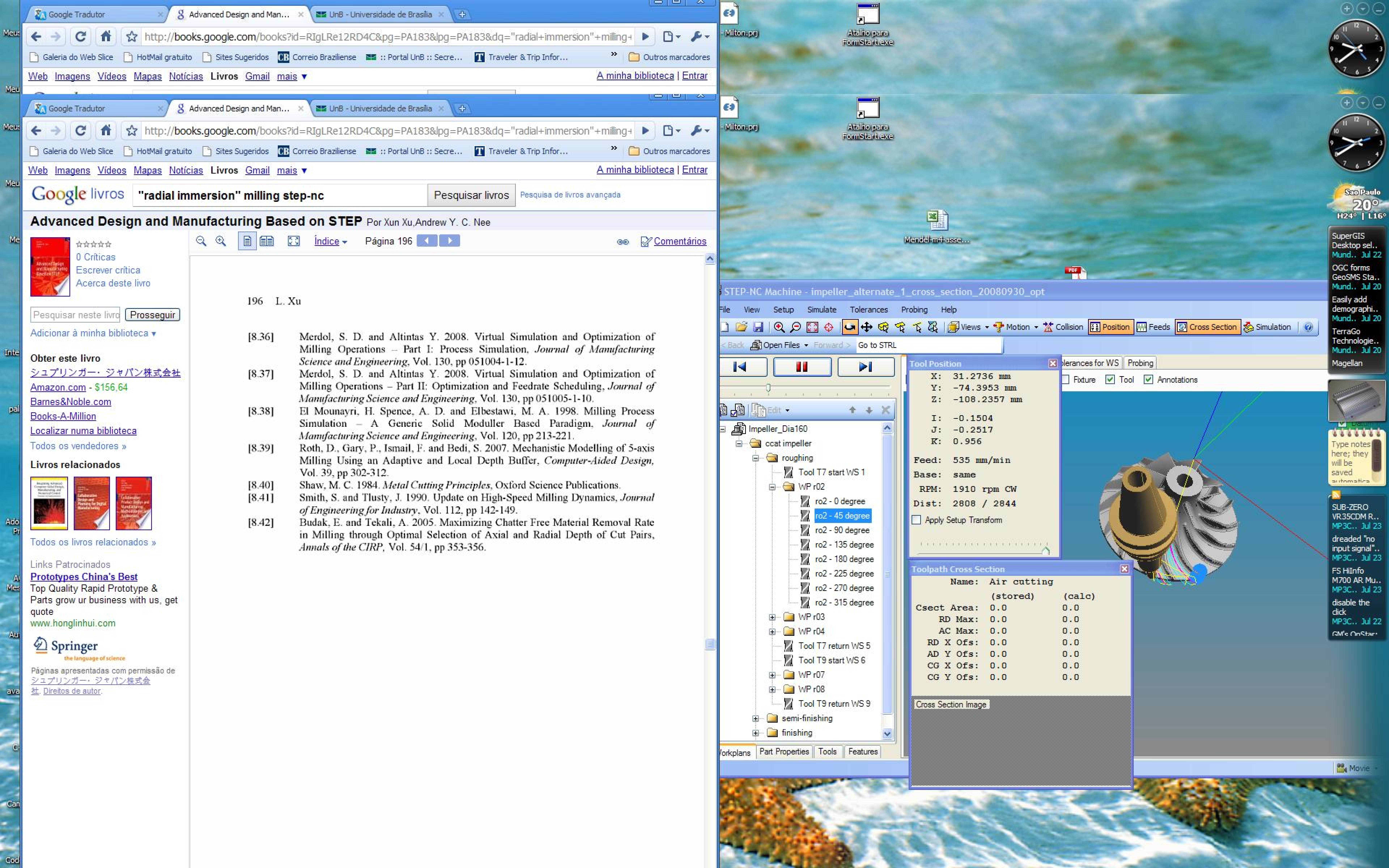
```
   X:  20.7137 mm
   Y:  -54.3311 mm
   Z:  -101.8608 mm

   I:  -0.0977
   J:  -0.5939
   K:  0.7986

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2373 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
       Name:  Line 22297
              (stored)     (calc)
Csect Area:   8.02         0.0
    RD Max:   12.18        0.0
    AC Max:   1.99         0.0
  RD X Ofs:   0.0          0.0
  AD Y Ofs:   7.88         0.0
  CG X Ofs:   3.01         0.0
  CG Y Ofs:   7.88         0.0
```

Cross Section Image



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STEP-NC Machine - impeller_alternate_1_cross_section_20080930_opt

Tool Position

```
X:  31.2736 mm
Y:  -74.3953 mm
Z:  -108.2357 mm

I:  -0.1504
J:  -0.2517
K:  0.956

Feed:  535 mm/min
Base:  same
 RPM:  1910 rpm CW
Dist:  2808 / 2844
```

☐ Apply Setup Transform

Toolpath Cross Section

```
       Name:  Air cutting
              (stored)     (calc)
Csect Area:  0.0          0.0
    RD Max:  0.0          0.0
    AC Max:  0.0          0.0
  RD X Ofs:  0.0          0.0
  AD Y Ofs:  0.0          0.0
  CG X Ofs:  0.0          0.0
  CG Y Ofs:  0.0          0.0
```