



Article

On the Use of PDF-3D to Overcome Spatial Visualization Difficulties Linked with Ternary Phase Diagrams

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Abstract: Despite the interesting applications that the PDF-3D offers in teaching, especially for subjects related to spatial comprehension difficulties, such a didactic tool is not well known in the education sector. Thus, a proposal of using PDF-3D in engineering studies is presented in this paper, specifically, in the field of teaching ternary phase diagrams (TPDs). The didactic resource—easy to design and easy to use—allows students to overcome spatial visualization difficulties linked with TPDs. According to students' opinions, the PDF-3D is an effective tool to use in any topic related to spatial difficulties and, in addition, is a friendly and easy-to-use tool. This fact and the simplicity of designing a PDF-3D make it a useful tool for educational aims.

Keywords: ternary phase diagrams; spatial visualization; PDF-3D; engineering education

1. Introduction

Since engineering studies are closely related to spatial concepts in many subjects [1–5] and it is proved that spatial ability skills can be improved through training [6–12], instructors are continuously developing both new educational methods and new tools for enhancing the students' spatial skills [13–18]. One of the topics covered in the study of materials science and engineering is ternary phase diagrams (TPDs) [19–21], for which students exhibit spatial comprehension difficulties [22]. Thus, several papers deal with this topic, looking for a solution by developing their own virtual and computational applications [23–27]. Several of these applications are designed for professional or research activities and, consequently, a wider knowledge is required to use them [23,26,27]. In such cases, designing these virtual applications is not a simple task, and a lot of time and specific knowledge of programming is required [23,27]. Additionally, special tools are needed, e.g., stereo display methods [26]. On the other hand, other applications are mainly focused on education [22,24,25], i.e., they try to help students to qualitatively understand the concepts of TPDs (without considering the equations representing curves in a TPD). This way, this type of application is easy for both instructors (easy to design) and students (easy to use).

In recent works [15,16], one of the methods to overcome spatial comprehension difficulties in engineering students involves the use of PDF-3D. Unfortunately, the use of this tool in the engineering education field is still unexploited, despite its clear advantages in the teaching–learning process; in fact, it is easy to design, easy to use, has good accessibility, and does not require any special software or hardware. Furthermore, this tool has not yet been applied in the teaching of TPDs—as far as the authors know. The aim of this paper is to fill this gap, by analyzing the applicability of PDF-3D in the teaching–learning process of TPDs. A design scheme that facilitates the reproducibility of a PDF-3D

is presented in this paper in order to help other educational staff to reproduce this type of didactic resource. Thus, since PDF-3D is both easy to design and easy to use, this paper shows the potential application of PDF-3D in the educational field for subjects requiring spatial skills.

2. Ternary Phase Diagrams in Education

Since phase transformations are important in many industrial processes involving heat treatment of metal alloys, the educational planning of both mechanical and materials engineering studies must include instruction on phase diagrams and, consequently, their associated microstructures. However, most of the educational textbooks only focus on binary phase diagrams (BPDs), which can be represented by a simple 2D plot, and they do not include, or provide scarcely any content on TPDs. Commonly, TPDs are represented by complex 3D plots with a triangular base, placing at the edges of the triangle the three elements of the metal alloy. TPDs are especially useful in the industrial field, since they help to analyze the microstructure (and, indirectly, the mechanical properties) of innumerable metal alloys composed of a mixture of three elements (e.g., Mo–Si–B), as well as ceramic and inorganic glass systems composed of three compounds (e.g., NaO–CaO–SiO₂). Because of the spatial visualization difficulties of the 3D TPDs, which can be especially complex in certain cases, a common technique used is the analysis of isothermal sections of TPDs (several online explanations can be found on how a given composition of elements A, B, C ($x\%$ A, $y\%$ B, and $z\%$ C) is identified or created in a TPD [28,29]). Furthermore, the TPD is simplified sometimes to a BPD, just considering an isoconcentration section of the TPD [30].

3. PDF-3D

The PDF-3D format allows one to open, visualize, and interactively move 3D models of diverse elements (buildings, machinery parts, and 3D diagrams) that were generated by different techniques, e.g., 3D scanning, photogrammetry, and modeling. It is just a file (*.pdf) that can be opened in a conventional pdf software and allows to easily transmit tridimensional information through the internet.

3.1. PDF-3D Design Process

Taking into account the potential usefulness that this computer application has in the education field, it seems interesting to briefly explain the general process used in designing a PDF-3D. This process includes several phases where different software must be used: (1) obtaining the 3D object by scanning or modelling it (for instance, by using Autodesk 3D studio Max), (2) converting the model into an OBJ extension, (3) converting the model into a universal 3D (U3D) extension by using Adobe Photoshop, and, finally, (4) generating a PDF-3D file (Adobe Acrobat). For the sake of clarity, a scheme of the design process is shown in Figure 1.

The intermediate step is mandatory if the latest version of Adobe Acrobat (Adobe Acrobat DC) is used, since such a version only admits the file format "U3D". However, previous versions of Adobe Acrobat allow to directly import models from the CAD modelling software. On the other hand, also other types of commercial software, such as "PDF3D ReportGen", "Tetra4D Converter", or "3D PDF Maker" allow direct importation from any CAD modelling software. However, the main shortcomings of these software are their cost (they are expensive) and their complex programming language (they require complex learning). In the authors' opinion, the process presented here is the simplest one using conventional software.

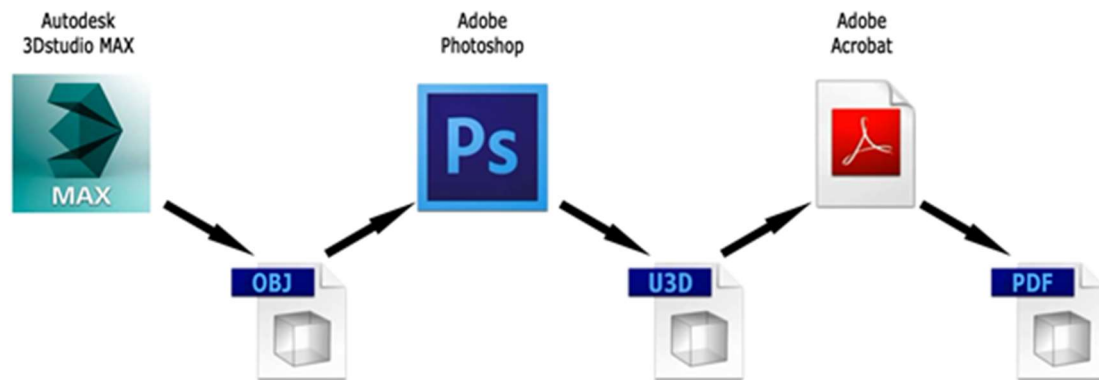


Figure 1. Design scheme of a common process for generating a PDF-3D.

3.2. PDF-3D of a TPD

In the field of mechanical and materials engineering, the design of a PDF-3D for a TPD starts by making a model of a ternary diagram with a 3D design tool, such as 3DStudio Max (Figure 2). In Figures 2–4, an example of a TPD, consisting of two binary eutectics and one binary isomorphous, is represented. The surfaces where a phase transition appears in the TPD are generated by using non-uniform rational B-spline (NURB)-type curves, according to a mathematical model widely spread for generating and representing curves and surfaces (Figure 3). Once the TPD is modelled, it is exported as an OBJ file (a common file type for software exchanging 3D objects), and later this file is opened as a 3D model with the well-known image software Adobe Photoshop (Figure 1). The file is then exported in universal 3D format (U3D), a file format that can be read by Adobe Acrobat, just when the final step is performed, including the U3D file and generating the PDF-3D file. The final appearance of the TPD is shown in Figure 4.

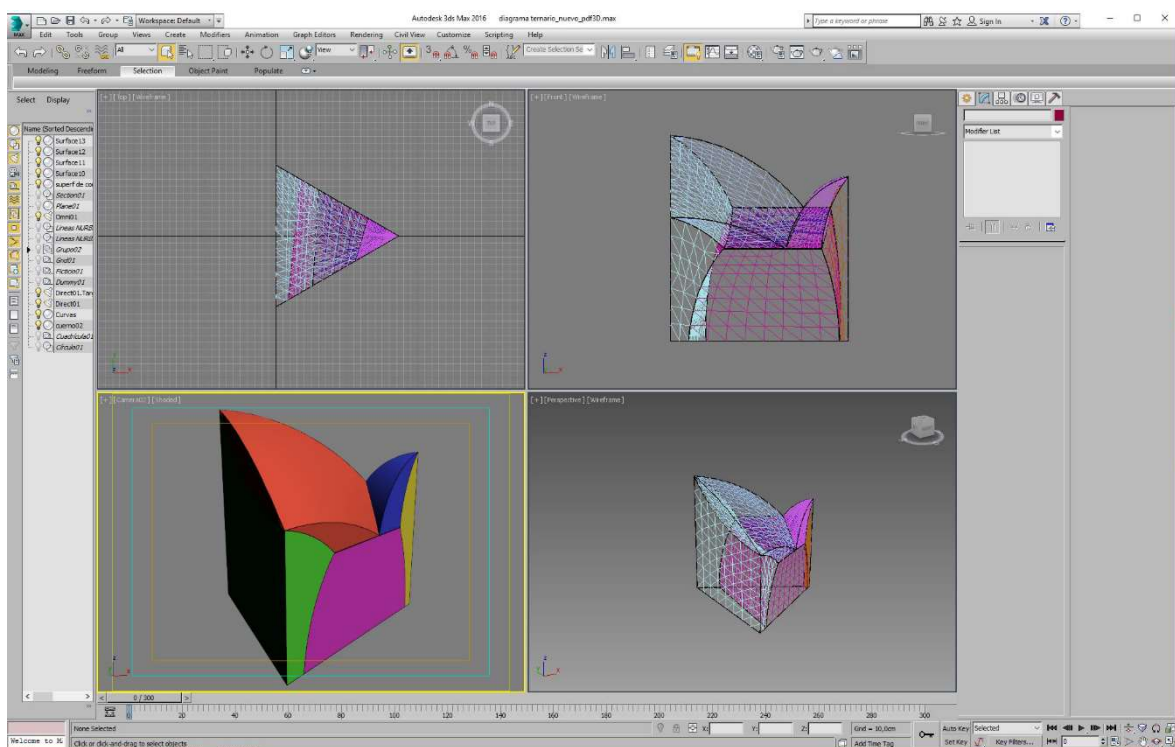


Figure 2. View of the ternary phase diagram (TPD) surfaces modelled in Autodesk 3DStudio Max.

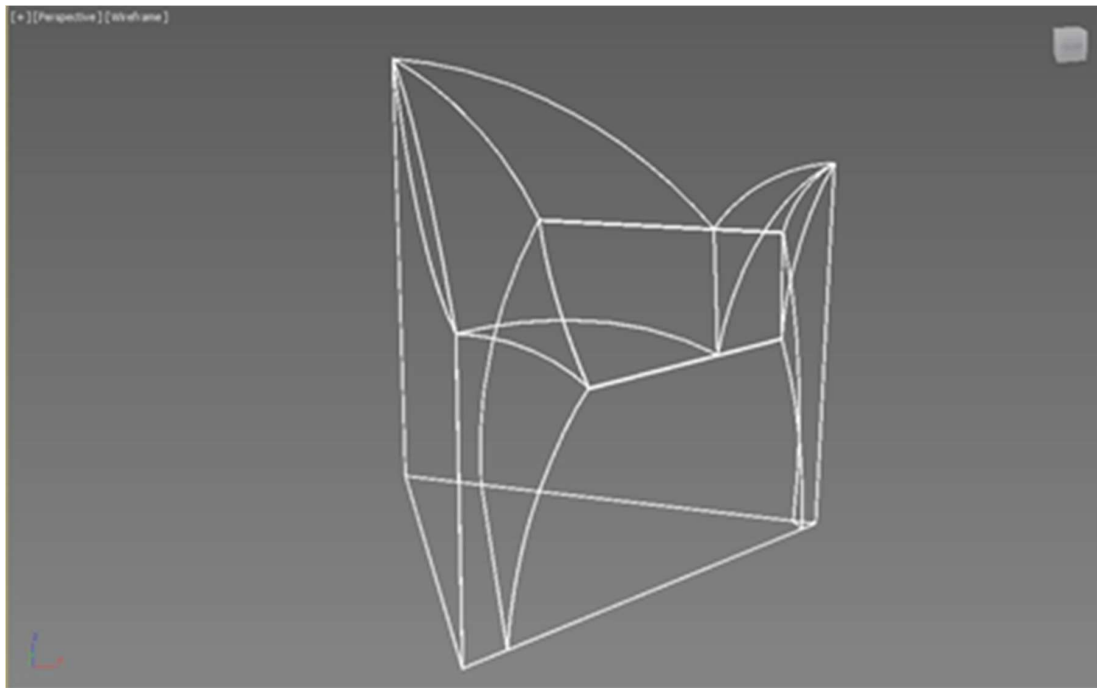


Figure 3. Non-uniform rational B-spline (NURB) curves defining a TPD.

In Figure 4, some of the PDF-3D features (useful for working with 3D objects) can be appreciated, namely, possibility of cutting and obtaining sections of the 3D object, turning and rotating the object, generating transparent zones, hiding zones, and even measuring distances in the model. Taking into account the serious spatial visualization problems in the student body, this tool is really useful for an introductory teaching of TPDs.

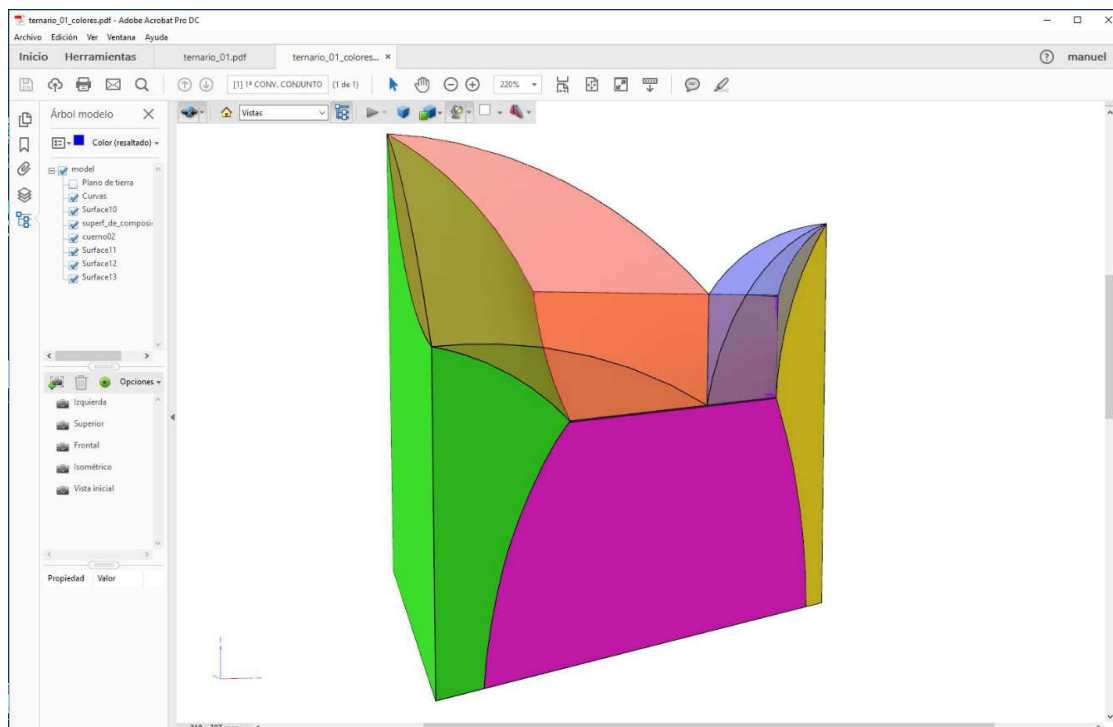


Figure 4. View of the TPD integrated in a PDF-3D.

4. Discussion

Nowadays, different options with increasing levels of complexity are available for developing an interactive computer-based tool to be used for explaining a concept involving spatial visualization skills. These tools can be classified into three groups: Group I: Applications directly programmed in a high-level language Group II: Applications created by using a specific development engine; and Group III: Applications that are obtained by using a standard software for generating 3D content, e.g., PDF-3D. For the selection of the group type to be used, the following issues must be taken into account:

- Difficulty in design and production
 - Need of scripts (thematic, technical, and artistic)
 - Need of technical knowledge
 - Required software and equipment
 - Time costs and working costs
 - Viability of the selected theme
- Degree of usability, interactivity, and complexity
- How the tool is distributed to the students
 - Unique file or a self-extracting file
 - Size of the file
 - Availability from the internet
- Need of equipment, software, and previous knowledge for using the tool

On the basis of these issues, applications included in Groups I and II exhibit a high difficulty in both design and development processes, since high-level technical knowledge is required, and a large amount of time and work must be applied [31]. Regarding the resulting tool, its size is large and, commonly, it is composed of multiple files, which makes the distribution to the students difficult. Additionally, high-performance microprocessors and graphical cards are necessary to run the tool. On the contrary, these tools allow a high level of interactivity, visual quality, concept development, and, even, content evaluation. Finally, these tools are more elaborated and controlled.

On the other hand, tools included in Group III (as in the case of PDF-3D) do not require a complex design, development processes, or a specific software. They just need the 3D model generated by a CAD software and a pdf reader software (e.g., the free Adobe Acrobat Reader), which are basic requirements for any engineering instructor. In addition to the clear advantage of the ease of design, this type of software allows an acceptable degree of interactivity and generates small-size files that can be easily distributed over the internet. The computer application PDF-3D allows to rotate and frame (to pan) the models, zooming, obtaining images, measuring, adding comments, hiding elements, selecting different points of view, modifying the type of visualization, changing the illumination, modifying the background, and making interactive sections of the model. Its main shortcomings are the low degrees of complexity, interactivity, and development. Furthermore, a commercial format developed by Adobe is required that, consequently, is limited to the Adobe specifications. Although interactivity is one of the properties most demanded by students in computer applications [32–34], the level of such a feature in Group III is enough for most of the virtual tools developed in engineering education (without professional purposes). Specifically, in the case of TPD, the PDF-3D allows students to spatially understand the different regions (3D geometry of the different phases) in an interactive way. Thus, this educational tool is a good complement to other online/interactive simulations that only explain simple 2D plots (isothermal sections of a TPD) [28,29].

4.1. Simplicity of Design (PDF-3D of a TPD)

PDF-3D could be considered as a promising tool to be used in the teaching–learning process of engineering degrees to overcome problems related to spatial visualization, which is a serious

matter for engineers who must carry out tasks during their student life [4] and also during their professional careers [35,36]. The design process of a PDF-3D is simpler than the design process used in other interactive computer-based tools, and PDF-3D is sufficient for the required aims in the teaching–learning process developed in engineering studies. Specifically, in the case of TPDs, PDF-3D is adequate for developing the basic design required in mechanical engineering studies, i.e., without precise mathematical equations that define the curves. The main aim sought by an instructor during the explanation of a TPD in mechanical engineering studies is achieving the spatial understanding of how such a diagram is formed, whereas the mathematical equations defining the curves of the TPDs are not important. Thus, this type of models is sufficient for teaching basic concepts regarding TPDs and helping students understand the spatial comprehension difficulties that the use of TPDs exhibits in a professional environment.

4.2. Educational Experience

The students' opinions after using the previously exposed didactic tool are presented in this section. To this aim, a quasi-experimental research was carried out on a total of 32 students enrolled in the Materials Science and Engineering course (in the Mechanical Engineering Degree). The survey questions were focused on, firstly, how helpful the PDF-3D tool is for students in the task of spatially understanding a TPD and, secondly, how easy it is to use such a didactic tool (Table 1).

Table 1. Questions included in the student survey.

Number	Question	Response
1	Do you think that the PDF-3D tool helps you to spatially understand the ternary phase diagrams?	Rate from 1 to 10
2	Do you think that the PDF-3D is an effective tool to use in topics related to spatial difficulties?	Rate from 1 to 10
3	How easy was it to use the PDF-3D tool of ternary phase diagrams?	Rate from 1 to 10
4	Could you indicate the positive aspects of using PDF-3D for teaching TPD?	

The obtained results revealed that the help provided by using the PDF-3D tool to spatially understand the TPDs was well rated by the students, as reflected in the average values of the answers to question 1 (9.3 out of 10 with a standard deviation of 0.24). Likewise, according to the students' answers to question 2 (Table 1), the PDF-3D is considered an effective tool to be used in other topics related to spatial difficulties (9.6 out of 10 with a standard deviation of 0.28). Furthermore, students gave the highest rating to the ease of use of the PDF-3D (9.9 out of 10 with a standard deviation of 0.20) and they highlighted other positive aspects of such a didactic tool, such as the availability to use it at home and the speed of opening the tool with a conventional computer.

It is worth noting here that the result of question 3 (9.9 out of 10) revealed how easy it is to use a PDF-3D, since mechanical engineering students generally give lower ratings to other virtual didactic tools which are easy to use [18,37,38]. This fact, together with the simplicity of designing a PDF-3D (compared with other didactic virtual tools usually designed with a more complex software), makes PDF-3D a promising application for the teaching–learning process in engineering studies.

5. Conclusions

Despite the didactic usefulness of the PDF-3D for subjects involving concepts with spatial visualization difficulties, there is a lack of research papers that show the use of this tool in the classroom. Since the PDF-3D tool is quite new, the tool and its potential applications are still unknown to the world of education. Authors consider the PDF-3D to be an educational tool with interesting

applications in any subject or topic related to spatial visualization difficulties, e.g., technical drawing, crystal lattices, biochemistry.

In this paper, a practical application using a PDF-3D in engineering studies is shown in order to teach ternary phase diagrams, which are characterized by serious spatial visualization difficulties. Both students and authors are really satisfied with the possibilities that such a didactic tool offers. Furthermore, this paper includes an explanation of the design process to create a PDF-3D, which is simpler and much easier to make than other didactic virtual resources, so that anybody can reproduce this idea, adapting it to specific applications.

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