

Software development for the evaluation of the ergonomic compatibility on the selection of advanced manufacturing technology

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Abstract. Advanced Manufacturing Technology (AMT) is one of the most relevant resources that companies have to achieve competitiveness and best performance. The selection of AMT is a complex problem which involves significant amount of information and uncertainty when multiple aspects must be taken into consideration. Actual models for the selection of AMT are found scarce of the Human Factors and Ergonomics perspective which can lead to a more complete and reliable decision. This paper presents the development of software that enhances the application of an Ergonomic Compatibility Evaluation Model that supports decision making processes taking into consideration ergonomic attributes of designs. Ergonomic Compatibility is a construct used in this model and it is mainly based in the concept of human-artifact compatibility on human compatible systems. Also, an Axiomatic Design approach by the use of the Information Axiom was evolved under a fuzzy environment to obtain the Ergonomic Incompatibility Content. The extension of this axiom for the evaluation of ergonomic compatibility requirements was the theoretical framework of this research. An incremental methodology of four stages was used to design and develop the software that enables to compare AMT alternatives by the evaluation of Ergonomic Compatibility Attributes.

Keywords: advanced manufacturing technology, ergonomic compatibility evaluation, ergonomic incompatibility content, software development, fuzzy axiomatic design approach

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1. Introduction

Advanced Manufacturing Technology (AMT) is recognized as one of the most valuable resources for companies in their quest for competitiveness in a globalized market. AMT is generally related with the use of computers during all the stages of the manufacturing process of a product; including design, manufacturing and management activities. Typically includes computer numerically controlled machines (CNC), Computer Aided Design (CAD) and Manufacturing (CAM), systems mediated by computer for storage of materials, Flexible Manufacturing Systems (FMS), among others [9]. This technology undergoes continuous, gradual but also radical changes in the industry, so tools and strategies for the proper selection of materials, processes, equipment and machines are required [15]. Commonly, decision makers (DMs) face situations in which it is necessary to plan, evaluate and select equipment from a variety of available alternatives. Also, decision making regarding the evaluation and selection of AMT involves a large variety of aspects that are difficult to be considered in its entirety.

This work presents the development of software following an incremental methodology of design. The general objective is to achieve a more simple, understandable, effective and efficient system for the potential users, and to enhance the application of The Ergonomic Compatibility Evaluation Model (ECEM) for the selection of AMT proposed by Maldonado-Macías [5]. This model contributes to the need of integrate ergonomic attributes into processes of evaluation and selection of AMT. This document is integrated of six parts; the first one is introductory, then the second one deals with the theoretical framework necessary for this work, which includes the basis for ergonomic evaluation model and the structure for software development. Then, the methodology for the software development is presented in the third part. The results describing the functions and parts of the software will then be presented in part four. Finally the conclusions and recommendations of the work are discussed and references are presented.

2. Literature Review

For Karwowski [21], ergonomics is a unique and independent scientific discipline that focuses on the nature of human-artifact interactions; it promotes the design and management of human-compatible systems. Also, this author proposed the sub discipline

called Simvatology that studies the compatibility of the human-artifact systems and it comes from two Greek words (Simvatotis = compatibility) and (Logos = reasoning about something). This sub discipline aims to discover the laws of artifact-human compatibility and develop a measurement for it. The EC is a construct used for the ECEM purposes and it is based on the concepts of compatibility between the human-system and the human-artifact proposed by Karwowski [19-21].

In addition, the Axiomatic Design Theory (ADT) developed by Suh [13], and particularly the use of the Information Axiom (IA) was included in the model. This axiom which was adapted and extended by Helander [10,11] and adopted by Karwowski [20-23] to address ergonomic aspects in technology; was also used for obtaining the Ergonomic Incompatibility Content (EIC). This is a measurement for the probability of an AMT design to meet Ergonomic Functional Requirements. This approach is based mainly in the extension and adaptation of the Information Axiom (IA). This axiom proposes the selection of the best alternative that has minimum information content. Based on this axiom in a fuzzy environment, the Ergonomic Compatibility Evaluation Model (ECEM) achieves the effective integration of Ergonomic Compatibility Attributes in a multi attribute decision making schema [2-4]. This model has its theoretical foundation mainly in the construct of Ergonomic Compatibility in a Fuzzy Axiomatic Design (FAD) approach.

According to Suh [13], with the intention of evaluate a given design, it is necessary to define the Functional Requirements (FRs) of a certain design, also the Design Range (DR) for each FR which represents the desirability of a system or product established by the designer or expert. Also, the System Range (SR) which represents what the system or product can really comply with such DR. The overlap between these two ranges defines a region that is called Common Area, and represents the probability with which certain system or product can meet the established requirements. In a fuzzy approach, data can be linguistic terms, fuzzy sets, or fuzzy numbers. If the fuzzy data are linguistic terms, they are transformed into fuzzy numbers first. Then all the fuzzy numbers (or fuzzy sets) are assigned to crisp scores. These numerical approximation systems are proposed to systematically convert linguistic terms to their corresponding fuzzy numbers thru several conversion scales proposed by Chen and Hwang [16]. In this way, the ECEM proposes to settle the Design Range (DR) denoted by the triangular fuzzy number (α, β, θ)

and to determine the System Range (SR) denoted by the triangular number (a, b, c) for each Ergonomic Compatibility Attributes (ECA). Figure 1 illustrates these areas using Fuzzy Triangular Numbers; the Common Area is also denoted in a shaded area. Ergonomic Incompatibility content for (I) alternative and j attributes is obtained by Equation 1. The Equation 2 defines Ergonomic Incompatibility Content affected by the importance weight assigned by the experts for i attributes.

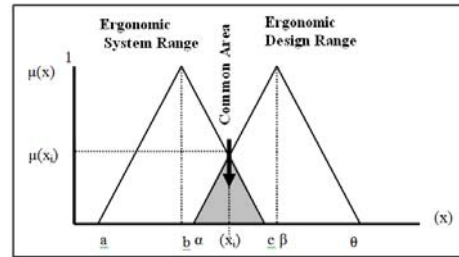


Fig. 1. Design range area, System Range Area and Common Area

$$EIC = \log_2 \frac{\text{Area of Ergonomic System Design (Triangular Fuzzy Number)}}{\text{Common Area}} \tag{1}$$

$$h = \sum_{i=1}^n (h_i) \tag{2}$$

2.1 Overview of the model (ECEM)

Ergonomic Compatibility Attributes (ECA) of the proposed model were determined by an extensive literature review and mainly based on the works of Corlett and Clark [6], Endsley [12] and the usability attributes proposed by Bruseberg [1] those were established as Ergonomic Functional Requirements (EFRs). They were divided into five main attributes and twenty sub attributes. Among the main attributes are: compatibility with human skills and training (A11), physical work space compatibility (A12), usability (A13), equipment’s emissions requirements (A14) and compatibility with organizational requirements (A15). The main attribute A11 includes two sub-attributes which are: compatibility with human skill level (A111) and training compatibility (A121). The main attribute A12 includes five sub-attributes: access to machine and clearances (A121), horizontal and vertical reaches (A122), adjustability of design (A123), postural comfort of design (A124), physical work and strength related to design (A125). The main attribute A13 includes seven sub-attributes: compatibility with design controls’ design (A131), compatibility with controls’ physical distribution (A132), and compatibility of the visual work space (A133), information load (A134), error tolerance of design (A135), functional allocation of (A136), and design for maintainability (A137). The main attribute (A14) includes four sub-attributes: temperature (A141), vibration (A142), noise (A143), Residual Materials (A144). Finally, the main attribute (A15) includes

two sub-attributes: compatibility with pace of work (A151) and compatibility with total work content (A152).

The Ergonomic Compatibility Evaluation Survey (ECES) proposed by Maldonado-Macias [3,4] was used to collect the data for the evaluation of these attributes on AMT and to obtain the relative importance of them from the participation of experts. Such evaluation applies to the selection of alternatives of AMT with a very similar or same manufacturing purpose (i.e. alternatives of CNC Milling Machines). The importance weight of each attribute for the model uses the AHP (Analytic Hierarchical Process) methodology proposed by Saaty [17]. The model is proposed for companies that face AMT selection processes and are interested in including ergonomic attributes in their evaluation. The software use will enables companies to create a database of AMT alternatives, perform systematic ergonomic evaluations of them and compare them to select the best choice that can satisfy ergonomic requirements.

2.2 Software quality requirements.

According to Pressman [14], to ensure computer systems efficiency, it is necessary to take into account certain aspects of quality, from the beginning of the process. Some of them are shown below:

- Maintainable: It must be possible that the software evolves and it continues to meet desirable specifications.

- **Reliable:** Software should not cause physical or economic damage in the case of failures.
- **Effective:** Software should not waste the resources of the system.
- **Usable:** The software must have an appropriate user interface and documentation.

During all the stages of this model these requirements were carefully pursued.

3. Methodology

The methodology developed in this work includes 4 stages of an incremental model. These are: analysis, design, coding and testing. As shown in Figure 2 all the information needs of the client and the purpose of the system are defined in the analysis phase, this phase will guarantee the system to meet the client needs. Later, in the design stage the system architecture is manufactured, defining how the system will be structured. Subsequently, entering the stage of coding,

the encoding of the entire design is made using programming languages. Then, in the test phase distinction among the results obtained of the system and those requested by the client is developed. Ending this stage the process can start again with the first stage and thus this way successively until the improved system design can be delivered.

Commonly, throughout the software development process it is not possible to design it as a whole, because there will be changes during the process, either in the case of research projects, adaptations and changes requested by the client may occur. For this reason, the incremental model is suitable for these cases where several iterations can be executed until the desired system can be obtained.

In this case the software development dealt with the following stages of the process by the incremental model proposed by Pressman [14], shown in Figure 2.

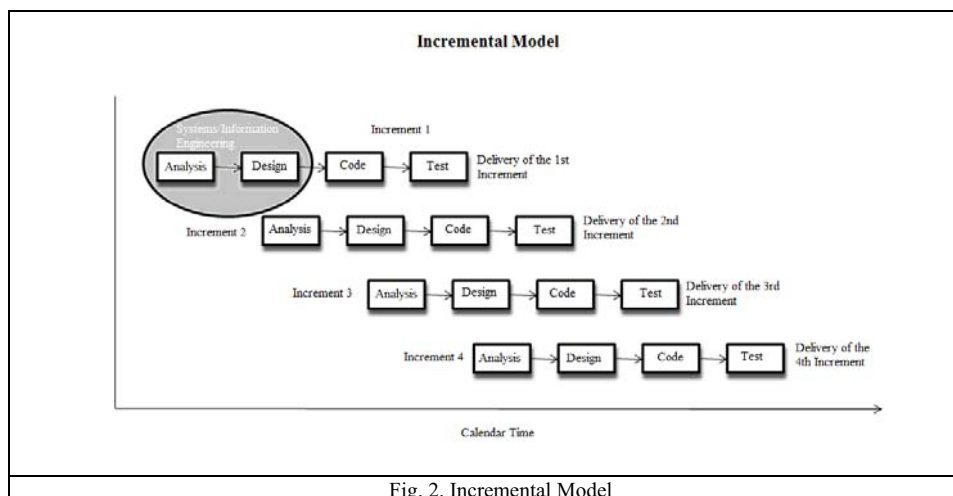


Fig. 2. Incremental Model

The previous stages and how they were used for the development of the software are described below:

- **Analysis:** In this stage, it is defined what the software should do according to the client needs and specifications. This stage describes the user requirements for the system and explains the functionality and the interaction between the user and the software application. For this case, the analysis phase consisted in analyzing the requirements of the client. One of them was the creation of a database for capturing and

processing the information from those companies interested in the use of software to assist their decision making processes about the selection of AMT. Also the needs of screens and menus to enter the generated data from the evaluation of experts and then how results can be shown for users were established. The most important part of this stage was to achieve the correct representation of the mathematical model proposed by Maldonado [5] for the ECEM for the selection of ATM.

- Design: This stage produces the structure of the system. This includes the database design, the screens and menus for input data and the application of the “user case” model for designing all the user-system interfaces.
- Code: This stage encodes the designed system. Code was developed in C# language within a Visual Studio ® 2010 environment. The works of Jiarratano, Sharp and Ross [7,8,18] were useful at this point of the investigation. Fuzzy Logic application was made by Matlab ® 2010 Software. This combination allowed handling the user interfaces and the database at the same time enabling to perform complex calculations for aggregation and compilation processes based on the Ergonomic Compatibility Evaluation Model (ECEM).
- Testing: At this stage, verification of the software took place. In this, the system must comply with what client’s requests. Several comparisons between the system results and previous results made by other methods help the validation of the generated functions. Functions to obtain the System Range Area, Design Range Area, Common Area, from triangular fuzzy numbers and membership functions were tested also using

AutoCAD ® against those created by the software. Results obtained from the Analytic Hierarchical Process (AHP) concerning the attribute’s relative importance or weights using the Expert Choice ® were compared with the results obtained from the system. Results were tested and the values were consistently correct.

4. Results

Results of each stage are explained in the following sections.

During the analysis stage and after several meetings with the user, the ergonomic evaluation model for the selection of AMT was clarified to design the system. The analysis was divided into 3 parts in order to have effective feedback on each one of the stages. These parts were: data acquisition, data processing and display of results. Also, in this stage the system was represented through a conceptual diagram shown in Figure 3.

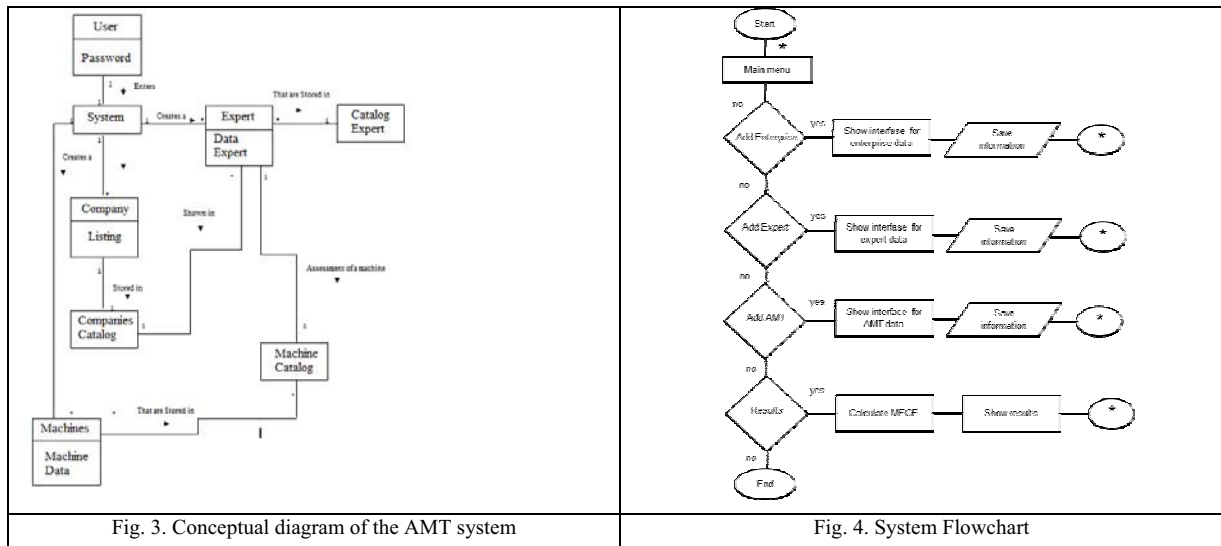


Fig. 3. Conceptual diagram of the AMT system

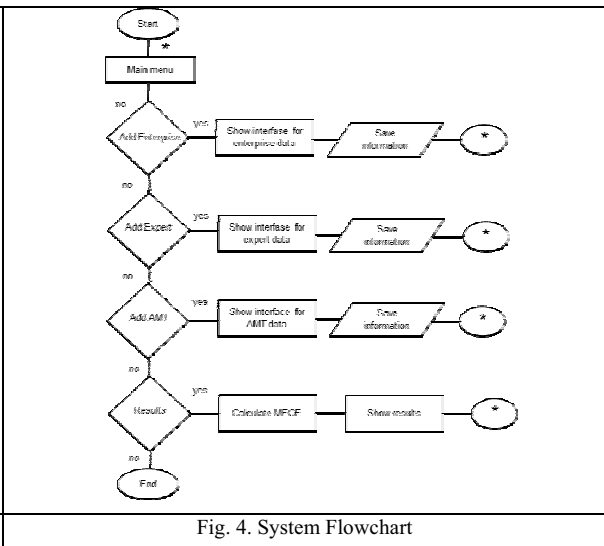


Fig. 4. System Flowchart

4.1 Basic functions flowchart

For this project, the model and the user interfaces, the database structure and the screenshots, were designed. The flowchart of the basic functions is a typical tool for this stage and it is shown in Figure 4.

In the first phase of design, main areas of the system are specified; this includes providing access through a main menu from which it could be possible to select the items the user needs. At this phase the information routes to be followed after running a command and the general operation of the system are designed.

This gives rise to several groups of menus with functions and procedures that are listed below:

- Main Menu: Responsible for being the connection among all system functions.
- Add Enterprise Menu: Capture information of a general nature such as personnel, infrastructure, process data acquisition equipment etc.
- Add expert menu. Capture information about the experts who will perform the evaluations about the alternatives.
- Add AMT menu. This area of the system enables to include a new alternative to be compared. Also, provides detailed information about the characteristics of alternatives (equipment) to be evaluated and compared. Also, this menu provides access to the evaluation process which enables experts to capture the scores and ranking of each attributes and sub attributes for each alternative. In this part, the Ergonomic Design Range, System Design Range will be captured via the experts' evaluations.
- Results Screenshot. This is the critical part of the system, because the information about the evaluations is presented. Also, calculations to obtain the Ergonomic Incompatibility Content (EIC) and the "spider" chart for the comparison are shown in this part. As a result, system delivers which alternative is the best in terms of satisfying established Ergonomic Functional Requirements.

This section displays results about the general comparison of alternatives and the detailed information of the evaluation of attributes and sub attributes separately this helps to analyze the final decision.

4.2 Data base design

The created database design contains the general information of the company, experts, alternatives, etc.

It consists of 6 tables correctly declared by name, also the field names and the type of data that they may contain. In addition, the information length assigned to each field was determined with the proper tolerance to execute changes on these fields. The structure of the database allows capturing the data; define the tables, fields, the type of data and the way by which the information contained in tables can be linked, recorded and retrieved from the database. Once the encoded and testing of this part was made on this phase, the next step was the creation of a digital version of the Ergonomic Compatibility Survey (ECS) proposed by Maldonado-Macías [3,4] required for data acquisition for the system. This version enables to acquire general information of the company, the experts' identification, equipment specifications and identification. Also, it contains the section where the evaluation process can be made, this part will be explained below.

4.3 Ergonomic Compatibility Evaluation Process

At this part, the evaluations made by experts are supported by the software. This includes the evaluation and determination of Design Ranges, System Ranges and the relative importance of each attribute and sub attribute.

The ergonomic evaluation for every Ergonomic Compatibility Attribute (ECA) is made for each alternative. Experts determine the Design Range (Design Range) and assess the accomplishment of this range by each alternative (System Range) for each attribute and sub attribute according to the ECS and the software menus using linguistic terms. The software systematically converts these terms into fuzzy numbers using appropriate scales.

Importance weight for every ECA is determined via pairwise comparisons according to the AHP methodology. The appropriate menu was designed by the software as well.

After the experts' assessment was made supported by the software, the Design Range (α , β , θ) and the System Range (a, b, c) are obtained for each attribute, sub attribute and alternative. This is made by appropriate aggregation processes integrated into the coding of the system. These data will be stored in the database, and will be transformed from the linguistic term of responses given by the experts who evaluated the alternatives of AMT to numerical data using fuzzy numbers. Once these ranges are obtained, it

necessary the creation of a function that will find the Common area which is needed to find the value of the Ergonomic Incompatibility Content (EIC) for each attribute and sub attribute.

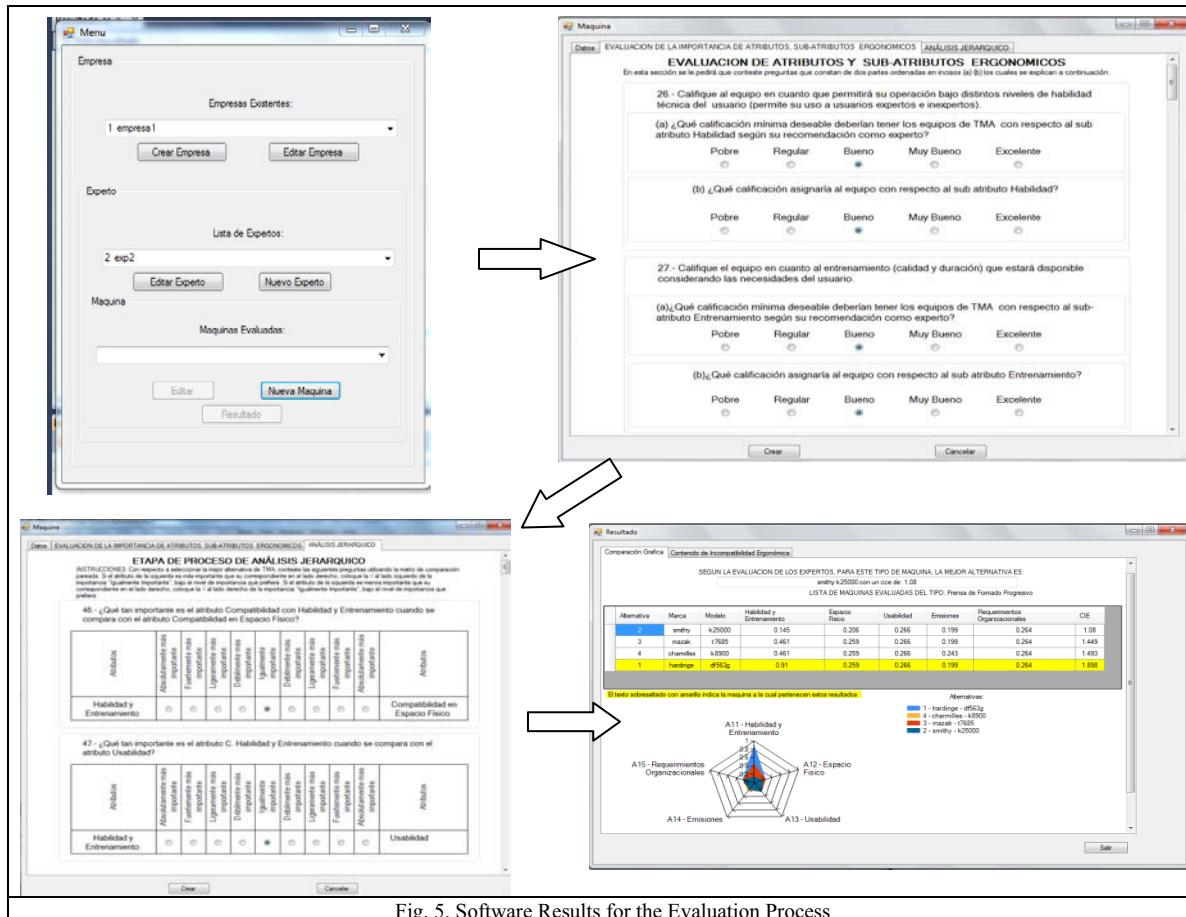


Fig. 5. Software Results for the Evaluation Process

Figure 5 shows the information workflow of the system, it includes four stages in screen menus, text is presented in Spanish. The upper left screen is used for capturing a new company; at this point the information about personnel, the experts, equipment (alternative) and general company's information. The upper right screen is used to capture the evaluation of the ergonomic compatibility attributes and sub attributes made by experts. Next, the lower left screen displays the menu to capture the rankings made by experts according the AHP methodology. Then, the data is stored in a table to obtain the relative importance or weight value of each attribute and

sub attribute w_i , this data is stored for each alternative and for each particular expert. These values will affect the calculation of the retrieved EIC by attribute and the total EIC for every alternative. Finally the software delivers the final results numerically and by a series of "spider" charts, this makes easier for user to find the EIC for each alternative and attribute separately. The alternative with the lowest total EIC is chosen as the best among the evaluated machines.

5. Conclusions

This proposal has been considered effective for the implementation of the EMEC which allows collecting and processing information about ergonomic compatibility evaluation of AMT. The model proposes a multi attribute structure and a fuzzy axiomatic design methodology that delivers the final result expected by the user. The proposed software is a technological innovation to assist decision-makers in the selection of the best alternative of AMT taking into consideration ergonomic attributes that have been obviated and underestimated by actual models in the selection of AMT. The application of the model using the system may contribute to make better decisions about AMT in its interaction with humans.

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Official sites for acquisition of the aforementioned software applications:

<http://www.mathworks.com/products/matlab/>
<http://www.expertchoice.com/>
<http://www.microsoft.com/spain/visualstudio>
<http://mexico.autodesk.com/adsk/servlet/home?siteID=1002155&id=7659874>