Six sigma has become a popular term in manufacturing and business world. Many success histories of companies that applied the methodology have been published. On the other hand, it is also important to report project failures and state some reasons for them. This paper describes a six sigma improvement project whose main focus was the optimization of a machining process of a specific part. It is believed that the project failed because the problem was related to the design of the product and the team was not able to rapidly identify this root cause and work it out. This difficulty caused a negative impact on the performance of the project concerning costs and deadlines. An analysis based on the perspective of DFSS was carried out, demonstrating the importance of a clear distinction between six sigma projects and DFSS, as well as the importance of the integration of both in the development of a holistic six sigma application program. The development of Design for Six Sigma is fundamental for the results of the six sigma philosophy as a whole. This work contributes to highlighting a new Critical Success Factor for six sigma projects and discussing some aspects that should be observed in order to avoid the presented failure.

Keywords: Design for Six Sigma, projetos de melhoria, Gerenciamento de Parâmetros críticos, retificação, estudo de caso
1. Introduction
Since the beginning of the last decade, when Six Sigma methodology first appeared, an increasing number of success histories of companies like Motorola, GE, ABB, among others, has been published. Some examples may be found in Kwak and Anbari (2006), Weiner (2004), Antony and Banuelas (2002). In general, the works highlight positive results and expressive gains achieved by the companies by means of the application of the methodology. There seems to be a smaller amount of studies presenting projects that have failed and pointing out some reasons for that.

In recent years, some specific applications in the area of product development have been presented. This methodology, named Design for Six Sigma (DFSS), has not been well examined yet: there are few works evaluating its applications and fewer theoretical models. Partially, this is due to the fact that DFSS is a recent version of six sigma methodology, also being a not so well explored area by managers and industrial engineers. Nevertheless, for the gains obtained in manufacturing and in the efficient delivery of the products to be long-lasting, they should be planned in advance, during the design phase. Thus, the theme should not be dismissed.

This paper presents a case study of a six sigma project whose main focus was the optimization of a machining process of a specific part. It is believed that the project failed because the problem was related to the design of the product and the team was not able to rapidly identify this root cause and work it out. This difficulty caused a negative impact on the performance of the project concerning costs and deadlines. The observations on the case motivated an analysis through the perspective of DFSS, demonstrating the importance of a clear distinction between six sigma projects and DFSS, as well as the importance of the integration of both in the development of a holistic six sigma application program. The development of Design for Six Sigma is fundamental for the results of the six sigma philosophy as a whole. As the case illustrates, investments in some improvement projects are just justified if the gained knowledge is applied to an entire product line or even to several ones, not being restricted to a local improvement in a specific process.

2. Barriers for the success of six sigma projects
Essentially, the six sigma program may be understood as a systematic problem solving method. In this sense, it is not new considering that these methods have permeated human history since remote times, even if in an intuitive fashion. However, there is a definite set of principles that characterize the methodology. In this work, six sigma is defined as a quality program, that is, a set of actions and projects oriented to the continuous improvement of products and processes, aiming to achieve high capability and conformity levels. Furthermore, it comprises a systematic project management methodology that integrates statistical and qualitative tools already known, striving to not only reduce the variability of processes, but also improve customer satisfaction.

Many authors such as Werkema (2002), Kwak and Anbari (2006), Fischbach (2006) and Pfeifer, Reissiger and Canales (2004) discuss some critical factors for the success of a six sigma program. The main factors highlighted by them are: senior management support, strong evaluation of the projects bottom line results, periodic reviews of the status and schedule of the projects, consistent awareness program of the six sigma activities and results, balanced portfolio of tools and best practices, availability of members and leaders for the projects, key-
Processes documentation, training of personnel, organizational structure oriented to the program, integration between the six sigma and other quality programs, selection of members with the right knowledge and skills for each project.

3. Fundamentals of Design For Six Sigma

Design for Six Sigma, or DFSS, is the application of six sigma methodology for product development, aiming to establish an integrated view among product, process and the several areas of the company involved with the product development process. Its role is “to build quality into the design” by means of the introduction, in the product development level, of reasoning and tools focused in prevention of the occurrence of errors. Thus, DFSS should be seen as a step forward in methodologies in the context of the evolution of quality, since it represents the transition from a reactive approach to a proactive one. (SIMITH, 2001).


Design for Six Sigma integrates three major elements to attain the goals of product development (low cost, high quality and rapid cycle time):

a) A clear and flexible product development process
b) A balanced portfolio of tools and best practices
c) A disciplined use of project management tools.

3.1. Critical Parameters Management

One of the key components of DFSS is the Critical Parameters Management (CPM).

Parameters may be defined as “measurable variables of the systems and subsystems […] that directly affect their performance and contribute to the attendance of the requisites of a product” (ROZENFELD et al., 2006). Briefly, requisites stated by the customer are converted into requisites of a product with the aid of QFD matrices developed during the design of the product concept. After that, the requisites of the product generate the requisites of the systems, subsystems and components. The next step is performing an optimization, i.e., applying robust project techniques to a set of parameters in order to attend these requisites. Thus, it can be seen that Critical Parameter Management must start at the design of the product concept phase.

The critical parameters are the ones closely related to the essential requirements of the customers. In general, there are few critical parameters amongst the whole set of parameters of a system. Thus, CPM allows narrowing the focus of product development, providing efficiency and also effectiveness in the use of resources because the efforts are oriented to the improvement of the few more significant parameters.

It is during the design of the machining processes that the attendance of the critical specifications, within the required tolerance range, must be assured. In other words, at this point, the compatibility between the specifications set on the project and the capability of the process should be verified.

The critical parameters are related to physical quantities, such as dimension, force, position, temperature, voltage, current, etc, which must be included in functional and mathematical models that represent the system behavior. As already said, series of tests must be carried out to optimize these parameters, making them less sensitive to the influence of sources of noise. The work of Creveling, Slutsky e Antis Jr. (2003) explains the CPM in detail and also develops the DFSS cycle applied to the development of technologies.
Rozenfeld et al. (2006) and Creveling, Slutsky and Antis Jr. (2003) highlight the existence of associated costs with each activity of CPM. Therefore, the application of the methodology as a whole is only justified for the development of products that use new technologies, such as the development of a platform, for instance. The CPM is a key component of DFSS since it directly applies the concepts of six sigma methodology, deploying the Voice of the Customer throughout the phases and gates of a product design process and converting it into final features of the products.

4. The case study

The company where the study was carried out is a manufacturer of mining and construction equipment. The project took place in a facility of the business unit responsible for the product line that yields the highest portion of the company’s revenue and represents its core business. Also, some components are sold to other business units.

Two field early hour failures set the focus on the manufacturability of a specific part, which presented nonconforming features. An internal grinding process is required in order to meet the specified tolerances. The process was presenting high scrap and rework rates. The pass rate varied from 73% to just around 10%. In short, tight tolerances were required and the process capability was not satisfactory. As a consequence, the facility was having difficulties in attending the demanded volumes for that part and the delivery deadlines.

A six sigma project team was assigned by the managers to address these issues. The initial goal consisted of improving the quality of the final machining process of the part, which would positively impact the productivity indices. The team carried out an investigation of the facts and pointed the following items as being relevant to the problem:

- The component was sold to another facility, that is, to an internal customer, which was responsible for the design of the part. After the occurrence of failures, this customer started to require 100% inspection;
- There are many interruptions in the machining process for the operators to take measurements as an attempt to avoid scraping too many parts.
- The machining parameters used in the process were varying within a significant range.
  There were no standardization; operators of different shifts were using different parameters.

After this analysis, an improvement phase was implemented aiming at quickly addressing some of the observed problems. The actions taken basically included changes in the inspection procedures, the use of different jig devices in order to reduce the error sources in machining and an agreement with the designers to increase some tolerance callouts. An observation that must be included is that the final product is highly complex. Therefore, failures are usually the result of a broad combination of interdependent factors, making difficult to root out individual causes of the problem and set tolerances that will guarantee the functionality of the product at a reasonable cost.

Another activity carried out by the team was the mapping of the complete manufacturing sequence of the component, called SIPOC map according to Werkema (2002). After that, a cause-and-effect diagram that included twelve factors was drawn. Under the factor Method, the dressing process of the grinding wheel was pointed out as a potential source of errors, among many others. Regarding Material, the team suspected that the quality of the parts produced by the previous process could significantly influence the quality that could be obtained after the grinding process.
The objective of the project was defined as the reduction of the grinding process variability. In subsequent meetings, another fishbone diagram was built listing the critical part specifications and tolerances, and associating them to the respective measuring machine or instrument.

As the next step, an initial list of input variables that could influence the outputs of the process was elaborated. The list included speed of the work head; speed of the grinding wheel; feed in radial directions; holding fixture; deflection of arbor; coolant temperature, mixture, flow rate and location; spark-out time; number of passes; grinding wheel dressing parameters; among others, resulting in 17 factors. The goal was the establishment of the relationships between input variables and each output, building a matrix structure. The list of variables was too long and the team was not able to define these complex relationships.

These two facts signaled the necessity of running a Design of Experiments, DOE, as a tool to determine the optimum levels of the grinding process parameters. This option was highlighted as a time intensive solution, that is, a solution that would require a reasonable amount of time and efforts. An expert in grinding process from the R&D department joined the team to reduce the number of input variables for the experiment. Two factorial experiments would be run. The first one would take 32 samples of the part, that is, the influence of 5 variables in two levels would be investigated, which comes to $2^5$ tests. If it were necessary to study more than 5 factors or inputs, incomplete factorial experiments would be carried out. This test would be performed aiming to provide an understanding of the main input variables that most affect the critical features of the part. After that, a second test would be run with 30 repetitions to each factor to optimize the parameters of the process, which means $30 \times 2^x$, where $x$ is smaller than 5.

In order to select the input variables and set their high and low levels, it was necessary, on one hand, to find out the parameters being used in the current process and on the other hand, to search the Best Practice parameters for the process.

To find the current grinding parameters, the operation was observed on-site and the operators were asked. The team faced some difficulties collecting this data. The numeric controller of the machine was obsolete and it was not easy to understand the relationship between the values of the machine inputs and the known grinding parameters. As already said, the inputs also varied with different operators.

Some research was conducted with the machine manufacturers to define the best practice grinding parameters. A guidebook provided a range of values for the main parameters (work piece surface speed, grinding wheel surface speed, and material removal rate). Additional parameters of interest, such as the dressing wheel parameters were obtained from the grinding wheel manufacturer.

At this point the project was interrupted for a month because it was hard to stop the production in order to carry out the tests, specially considering that some deliveries of the part were already late. The observations on the case were finalized before it could be finished due to practical restrictions on the schedule of this work. Thus, it was not possible to analyze the results of the Design of Experiments. However, more important than this analysis is the fact that the time frames of the project phases had already exceeded the expected deadlines. From the beginning of the project to this point, ten months had passed. This aspect will be discussed in more detail in the next section.

5. Analysis of the case
The first fact to be highlighted is the lack of a clear definition of the DMAIC phases of the project. A schedule with estimate deadlines for the phase gates were not clearly stated. If these deadlines were rigorously defined and followed, and if the project management were oriented to the control of deliverables, the time frame of the project could be probably shortened, which would positively contribute for the overall performance of the project. The importance of the management by deliverables is highlighted in some reasearches in Product Development Process, such as in Rozenfeld et. Al. (2006) and in some six sigma publications, as in Werkema (2002) e Pande Neumann e Cavanagh (2000).

A complex issue that was observed is the conflict between tight tolerances specification and process capability, which constitutes a typical dichotomy of manufacturers of mechanical parts. In general, the designers tend to set conservative tolerances in order to avoid failures. High-quality surfaces require longer machining time. On the other hand, manufacturing processes are driven by achieving high productivity levels. This paradox could have been solved in the manufacturing processes design phase, with the aid of DFSS tools and Critical Parameters Management. The physical distance between the facilities involved in the problem, which belong to different business units, in this case, contributes to the lack of integration of the design team with the manufacturing team. However, a more relevant cause for that is the organizational structure of the company, which is predominantly functional and not oriented to processes. Although the fact that the component is a core competence of the company, no optimization methodology was applied to it.

The first action to be taken, in this case, could exactly be integrating the design with the manufacturing experts of both facilities. Thus, the manufacturing experts would join the design team in the phase of detailed project, when it would be necessary to set the tolerances and process plans.

At first, it was not evident to the team that the main cause of the problem was related to the process of setting the specifications without considering the manufacturing capabilities. In addition, all the designed experiments strove to optimize the grinding process of a specific component using a specific machine. Extending the knowledge learned to other projects was not a primary intent of the project.

The perception of the problem as being located in the interface of product design and manufacturing processes brings to the scene discussions about the adequacy of the project scope. The analysis of the problem and the design of experiments pointed out the need of a deeper study about grinding technology, which is too long for a project in the manufacturing area, that usually demands fast and effective solutions.

In addition, the availability of some members and the Black-Belt of the project was restricted due to other activities and projects. This is highlighted as a Critical Success Factor for the six sigma methodology. These two components combined probably influenced to some extent the team’s motivation and perspectives of short-term success. This context is presented in Figure 1.
Figure 1 – Structure of the six sigma methodology application and main difficulties faced in the observed project

It may be a naive approach just to point out the lack of availability of members and leaders or the lack of management support as the causes for six sigma projects failures. Some observations show how the inefficiencies in the product development process may require significant efforts in six sigma projects after the product was approved for manufacturing or even launched. Indeed, it may be crucial that the product development team take part in some improvement projects.

The DFSS methodology is an option to approach the problem, aiming to provide a structural solution rather than a particular one, that is, providing a consistent capability assessment and a better understanding of the manufacturing technology.

With this methodology and the CPM, the technology of the process would be developed during the design of the manufacturing processes, still in the product development level. In this case, an investigation of the critical parameters of the process would be carried out. Therefore, the team would start the project from a certified basis of that technology, needing to adapt it to the boundary conditions required for the specific application, that is, the machining conditions for the specific part.

The analysis of the case indicated that the DFSS methodology should be applied to the development of technology, as mentioned in the literature review in section 3.1. In this case, the scope would not be a new technology, but rather a traditional one that is critical for the company and is used in many parts. That would be an answer to the demand of a systematic knowledge about the process technology, which was noticed during the project execution. It should be noticed that the objectives of the DOE and the proposed division of the tests into two phases are very similar to the DFSS proposal as described at Creveling, Slutsky e Antis Jr. (2003) approach. The phase 1 of the tests defined by the project team has similar objectives to the “Development of Technology Concepts” of the I’DOV cycle, whereas the phase 2 of the experiments may be compared to the “Optimization”- of the referred cycle. Figure 2 presents the proposed approach for the case and its potential advantages.
If this solution just mentioned was adopted, two different projects could be carried out. In the first one, people from the R&D area would build the functional model that represents the technology and would optimize its Critical Functional Parameters for a range of values through series of tests, according to DFSS paradigms. The advantage of this is that these members would be more available to focus on the project and the optimization, and time availability of the team would not be a barrier anymore. From this knowledge basis, the manufacturing team would carry out the improvement project, which is expected to be much faster than the observed project.

The implementation of this solution certainly requires investments in infra-structure and resources such as laboratories, machines, equipments and measuring systems to support the methodology. Nonetheless, grinding is a critical process and many lines of components may take an advantage of this development. Thus, the costs of implementation may be split among a reasonable set of products.

Another advantage of investing in resources for research is that this physical structure would be easily available, that is, there would not be a need of using equipments destined to the production activities. This difficulty of allocating equipments, such as machines, to perform the tests was faced by the team, as described in topic 4, and it contributed to a unnecessary extension of the project time frame. With the DFSS, this problem would be minimized since, as previously said, the technology would be already certified for a range of values, and the team would just transfer it to the required application.

Knowledge management is a key factor with which companies, in general, present some difficult to deal. In this sense, the application of six sigma and DFSS methodologies help to build a data base of technology and other critical parameters related to the company’s main activities. The process of storing and retrieving information should be carefully planned. In some companies, a lot of knowledge is lost due to lack of formal or incorrect registration, or to difficulties in querying and retrieving data. DFSS and the six sigma projects have their contribution in converting tacit knowledge into explicit one, and, consequently, may be seen as additional tools for organizing and spreading knowledge.
5. Final remarks

The case study showed the importance of a careful definition of the scope of six sigma projects and a careful assignment of the people. The problem faced by the team demanded a deeper study about grinding and machining technologies, with an extension and goals that were not compatible with the scope and time frame of this kind of improvement projects. In other words, the broad scope, the restricted availability of members and the difficulty in integrating the areas involved with the problem led to and excessive long time frame and compromised the effectiveness of the project.

The case also indicated the need of aligning the six sigma methodology applied to improvement projects with the Design for Six Sigma, in order to obtain synergy. This means training the teams to apply both methodologies and including topics of DFSS and its relationship with six sigma in the Black, Green and White Belt trainings. The Black Belts’ training should be even more detailed. This would give way to the identification of problems and root causes such as the ones presented, and would avoid waste of time and failures due to the incorrect definition of the scope.

This work is a case study and cannot be generalized. However, it contributes with the identification of an additional Critical Success Factor for six sigma projects that, according to the literature review presented, is not usually reported in other researches. This factor is the badly delineation of the scope, when it encompasses functional modeling and optimization into an improvement project. This is an aspect that should be explored and validated through survey researches about six sigma implementation. Furthermore, this paper emphasizes the potential benefits that could derive from the implementation of DFSS, such as the reduction of the projects time frame and the increasing of their effectiveness. The costs with experiments would likely be reduced because the projects would share a certified technology basis. Finally, the DFFS presents the advantage of being a preventative, or proactive approach for the problems.

The main recommendation for future works is a case study of DFSS implementation in the development of a product and a technology, aiming to observe its integration with the six sigma methodology applied to process improvement and the possible positive results of this integration. This is a subject that certainly deserves attention since there is a small volume of Brazilian companies that apply DFSS and few works in this area.

6. References


8., 2006.

