EVALUATING THE ACCURACY, TIME, AND COST TRADE-OFFS AMONG ALTERNATIVE STRUCTURAL FITNESS ASSESSMENT METHODS

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Abstract

Development project lead time and cost are of growing importance in the current global competitive environment. During the development of physical products, one key task is often the assessment of a component's structural fitness. This paper examines the trade-offs that occur among different methods of assessing structural fitness and their associated accuracy, costs, and lead times. Results show that physical prototypes require significantly more time than analytical prototypes, where only simple calculations or finite element analyses are used. Trade-offs are further illustrated using a case study, which examines the need to meet lead-time and budgetary constraints. In this case, it is shown that it can be preferable to choose a more accurate method even if it has a higher cost and lead time. The inability to escalate to a more accurate method later and still meet time and budgetary constraints can prescribe choosing a more accurate method initially, assuming that the time and budgetary penalties for that method are not too great.

Introduction

Development is the process of creating technically feasible solutions in order to meet customer needs. In today's technologically driven world, the importance of development to the success or even survival of a firm is unquestioned. The return on investment for research and development has been shown to be more effective than capital expenditure at boosting various financial metrics [1]. However, it is not sufficient that the product-development process be effective, it must also be quick. Development lead time can affect the commercial and financial success of a product [2]-[4]. Some companies even use time-to-market as a key product development metric [5]. There is a potential conflict between trying to complete a development project quickly and producing a superior, or even acceptable, product. Design iterations increase product quality, but do so at the expense of increased lead time [6].

It is often said in product-development circles that "we never have time to do it right, but we always have time to do it twice". This remark arises from the tension between the desire of technical professionals to engineer "perfect" products and the business reality of needing to deliver those products in an efficient and cost-effective manner. There are usually alternative methods available to determine the acceptability of a given design solution. These range from simple analytical prototypes—such as stress calculations or the use of hand books—to comprehensive physical prototypes such as creation and testing of entire products [7]. Rapidly advancing technology in computer-aided design, manufacturing, and engineering allows for several aspects of a product throughout the realization process to be analyzed virtually. The selection of alternative assessment methods through the development process dictates alternative costs and lead times. This initial selection can also affect the costs and lead times associated with alternative assessment methods used during iterations.

There has been significant research regarding both product- and project-related risks. Product risk is defined here as an unacceptable design solution – something that does not meet technical or customer requirements. Project risk is defined as the failure to conform to time and budgetary constraints. Previous research has examined the effects of iteration on cost and lead time [6], [8]-[9]. These studies did not include the tendency to escalate to more accurate assessment methods in the event of an assessment failure. Assessment failure is defined as a method signaling an acceptable design solution, when in fact the design solution is not acceptable. This would be a Type II error. If a relatively quick and inexpensive assessment method resulted in an assessment failure, it is likely that an alternative method with putative higher accuracy will be chosen next. This switching can require significant additional time and cost.

This current study will look at 1) the tradeoffs associated with these alternative methods and switching costs, 2) a summary of related work in the areas of project lead time, risk, and simulations, 3) a presentation of the methods and results of a design and test project, 4) a case study used to illustrate the usefulness of the results, and 5) the limitations and conclusions of this current study.

Related Work

Product development lead time has long been a research focus and has been examined from various perspectives. Some of the earliest work examined the distribution of labor over the course of a development project [10]. The effects of how tasks overlap [11] and, as noted previously, iterations have been examined. Project team resources [12] and organization have also been analyzed [13]. Product complexity and newness have been shown to increase development lead time [13]-[14]. In addition to understanding the product and project factors that affect lead time, unexpected changes in schedules or resources (project risk) have also been examined.

A significant amount of research has focused on assessing and mitigating project risk, which is usually related to lead time and budget. These previous research projects attempted to reduce unexpected delays by better understanding their causes [15] or providing frameworks that recognize risks and aim to mitigate their consequences [16]-[18]. Project simulations based on previous project data were used to examine budget and risk minimization strategies [19]. In addition to project risk, there is also technical or product risk. Similar techniques were used to assess product risk, such as examining the failure of similar products in the past [20]. Risk identification and mitigation techniques were also used for product risks [21]. Prototypes were suggested as a way to reduce both product and project risk [22]. The use of computer simulations may be another way to reduce risk and possibly decrease lead time in development projects.

There have been significant advances in computer simulation over the past two decades. Some authors have predicted that computer-aided engineering will eliminate the need for prototypes [23]. However, even a prominent proponent of finite element analysis (FEA) has expressed reservations; over a decade ago, the founder of ADINA (a FEA company) expressed concerns about the growing number of designers using FEA software [24]. This was before programs such as COSMOS (SolidWorks), Mechanica (ProEngineer), and DesignSpace (ANSYS) made FEA more accessible to designers. In addition to concerns about the training and expertise of those using FEA tools, there were questions about the reliability of the numerical simulation tools themselves. The complexity of building a reliable computer prediction was noted; when empirical data is absent, there is ignorance [25]. A necessary step of producing a reliable model is the comparison of the observed physical event with the prediction of the mathematical model; this is referred to as validation [25]-[26].

Unfortunately, this validation processes can require a significant amount of time [27]. Therefore, some trade-off must be made between lead time and method accuracy; one must choose among quicker methods, validated numerical methods, or gathering empirical data. This decision will have an impact on both product and project risk. This study presents an explicit quantitative assessment of alternative assessment methods. The relative accuracy of two analytical prototyping methods is compared to the results of a physical prototyping method. This relative accuracy is then compared to the engineering effort (in person-hours) required to produce these results.

To illustrate the impact that assessment method selection can have on product and project risk, a case study is also detailed in the next section. This case study examines three alternative methods that were used to determine if a design solution is acceptable. The case study also incorporates the role of iterations and unique assessment-method escalation. The effect of assessment method on project-related quantities, e. g., lead time and budget, is illustrated and the product and project risk associated with the methods are presented.

Exercise and Case Study

To examine the effect of alternative data gathering methods on product and project risk, a senior design project was commissioned to mechanically evaluate a simple component. A team consisting of three students designed, performed finite element analyses, manufactured, and tested the specimen. The students were asked to design a specimen that was simple enough to structurally analyze without the use of FEA and that could be machined using manual machining equipment. Three points of interest were selected to examine the mechanical behavior of the specimen when under a load. The specimen, points of interest and loading configuration are shown in Figure 1. The span of the specimen is approximately 15cm and was manufactured from 6061 aluminum. The lower portion of the specimen was assumed to be constrained, as it would be in a fixture as shown in Figure 2. The students were asked to evaluate the specimen using three methods: simple stress calculations assuming only bending, finite element analyses, and the use of strain gages on a manufactured aluminum prototype. The students were asked to keep a diary of the time that they spent performing each of the tasks throughout the project.

Initially, the component was modeled in Pro|Engineer CAD software. Once the design for the component was finalized, the students began assessing its mechanical behavior. It was decided to test the component using 3kg, 5kg, and 7kg loads. The loads would be hung from the end of the specimen to produce a bending deformation, as shown in Figure 2. Given that the component was loaded in simple bending, it was assumed that at the three locations of interest only the principal stress, as a result of bending, would be relevant. The next step was to evaluate the mechanical behavior of the specimen using the alternative methods. The first method consisted of performing a simple bending stress calculation using:

$$\left(\sigma = \frac{My}{I}\right) \quad (1)$$

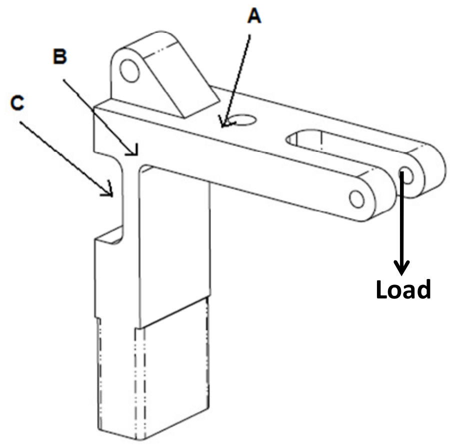

Figure 1. Diagram of specimen detailing points of interest.

Figure 2. Specimen in testing fixture

These calculations took into account the stress concentration caused by the hole at point "A" in Figure 1. Next, Pro|Mechanica—the integrated finite element program within Pro|Engineer–was used to perform the finite element analyses of the component assuming the previously mentioned loading conditions. The simulations were run and the predicted stresses at the locations of interest were tabulated. Finally, a prototype component was machined using a CNC mill. This required the generation of a numerical control program, or g-code, that was generated using the FeatureCam program. The material was pre-cut to near net shape to minimize machining time. The prototype specimen was then instrumented with strain gages at the locations of interest and loaded in the aforementioned manner. Three samples were taken at each location for each load. These strain results were then averaged and used along with the elastic modulus of 6061 aluminum (70 GPa) to determine the stress at the points of interest; this assumed only linear elastic bending.

For the purpose of this study, the results of the physical prototype test were assumed to be the baseline. The strain gage results were assumed to be the most representative of the physical event. Figure 3 shows the relationship between the time required to complete a given analysis and the deviation from the baseline result. Overall, the majority of the results were within 20% of the baseline. The notable exception is the finite element analysis results at location B. These results predicted stress in this location that were almost four times greater than the baseline result and the simple stress calculation. With the exception of this result, all other results were within 20% of the baseline. The majority of the results also produced what would be considered a Type I error with respect to the baseline, i.e., they predicted higher stress than the baseline. This is usually the preferred type of error in structural fitness evaluation methods as an over-engineered design is usually preferable to one that fails, though there are exceptions such as insertion or removal force for a snapfit. The only method that produced appreciable Type II errors was the simple calculation method at location B; the FEA method error at location C was less than 1%. But even this method's 16% deviation from the baseline would be overcome with an extremely modest safety factor of 1.2. The overall trend showed that slightly more deviation resulted from methods that had a lower completion time, excluding the FEA outlier at location B.

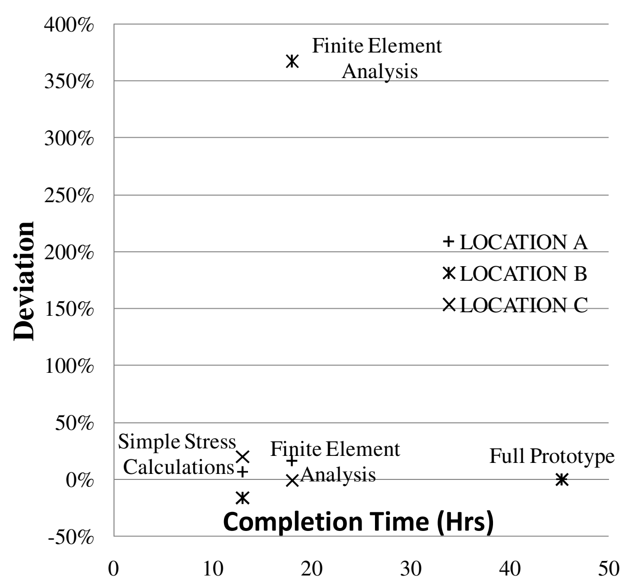

Figure 3. Deviation of stress results from those of a full prototype as compared with a full prototype tested at three locations and compared to test data gather time (hrs).

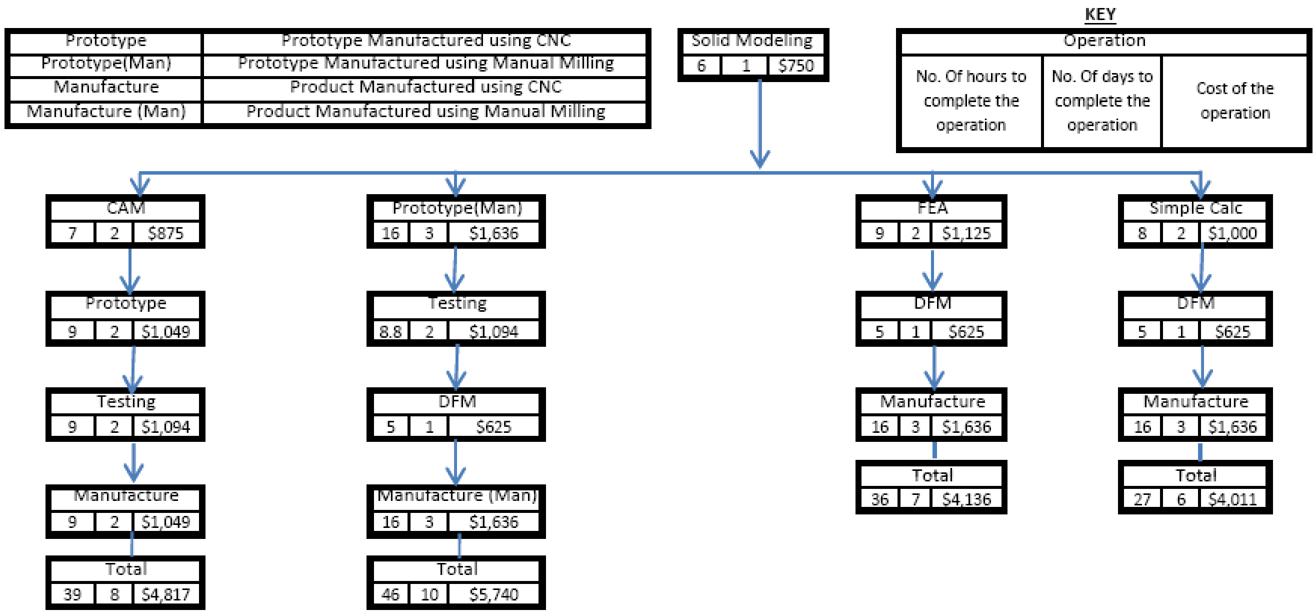

Figure 4. Process flow for alternative data gathering and manufacturing methods for the component.

While in this case the lower time-investment assessment methods produced results that compared well with the baseline, that may not always be the case. As such, the effect of product risk on project risk was still evaluated. For purposes of this project, it was assumed that the initial design would be evaluated for mechanical behavior—as detailed above—then manufactured and delivered for installation. If the component met the structural requirements as expected, the project was deemed complete. If it failed, a component that met the structural requirements had to be redesigned and delivered at no additional charge. The budget and lead time for the project were $7500 and three weeks—15 business days, respectively.

Figure 4 shows the process plan for alternative methods of evaluating and delivering an acceptable component. All methods begin with design selection and solid modeling. The three mechanical behavior methods are detailed above: simple calculations, finite element analysis, and physical prototype testing. There are two alternative methods of manufacturing the component for both the prototype and final production: the machining can be done with a CNC mill, requiring a computer-aided manufacturing – CAM – numerical control program or it can be done manually. These two methods are noted in the process plan. It was assumed that if the manual milling operation were chosen, a design for manufacturing (DFM) analysis would be performed in order to determine a process plan and proper feed rates. The time durations shown in Figure 4 are those reported by the senior design project team. The two exceptions were the durations for the DFM analysis and the estimation of the manual machining time, which were estimated by the authors using Boothroyd et al. [28].

It was assumed that both machining and engineering labor would have an efficiency of 60%; direct production work is being done 60% of the eight-hour work day. The fully-burdened hourly wage for engineers was assumed to be $75; the fully-burdened wage for a machinist was assumed to be $50. The wage and efficiency numbers are averages for engineering and production personnel found in Johnson and Kirchain [29]. There was also a $28 hourly charge for the CNC mill and a $16 hourly charge for the manual mill. The hourly charges for the machines were based on purchase costs of $175,000 for the CNC mill and $100,000 for the manual mill. It was assumed that these mills would operate 1000 hours per year and were amortized over a 10-year useful life using a 10% cost of capital to take into account the time value of money [30]. Materials were assumed to cost $75 per part; this was based on the actual cost of material used for the project. The cost of each operation and the total for each alternative method are shown in Figure 4.

As expected, the simple calculation and FEA methods were less costly and could be performed in the shortest lead times. The two full prototype methods were more costly and required more time with the method that does not use the CNC mill, taking the longest and being the most costly. All methods were within the lead time and budgetary constraints outlined above, assuming the assessment methods were accurate and correctly predicted an acceptable design. However, if the component were installed and failed, the component would have to be redesigned and retested. As mentioned above, this retesting would probably involve escalating to a method deemed to be more accurate. In the case of the simple calculations—the only method to produce appreciable Type II errors—escalation to the FEA method would require an updated design, an FEA analysis, the manufacture of the new component, and would require an additional six days and approximately $3000. This assumed that the FEA method would take one-third the time of the original and that the DFM could be omitted.

This additional time and cost, combined with that of the original method, would be very close to the time and budgetary constraints. It was not possible to escalate to the manually manufactured prototype method and still meet time and budgetary constraints, which were an additional time of 9 days and an additional cost of $4,600. It would be possible to escalate to the CNC-prototyped component and still meet the lead time constraint, but not the budgetary one of an additional time of 7 days and an additional cost of $4,300. Overall, it would probably be preferable to choose one of the physical prototyping methods, even though they have longer lead times and cost more. It would be very difficult to escalate from one of the lower-cost and shorter lead-time methods and still meet the time and budgetary constraints in the event of Type II errors.

In summary, product risk is shown to have a significant effect on project risk and should be mitigated through the use of high-accuracy assessment methods in the presence of stringent time and budget constraints. This study examined a specific case and made numerous assumptions; as such, the results should be interpreted within certain limitations. These are discussed in the next section along with some conclusions.

Limitations and Conclusions

There are several limitations through which this work should be interpreted. First, a single and relatively simple product was examined for structural fitness. This allowed for a range of assessment options to be evaluated. In some cases, the ability to manufacture and test a component would not be feasible; in those cases, only simulation methods would be available. Second, this study assumed that all of the results from the various methods would be interpreted in a similar manner. It is possible to mitigate both the product and project risk associated with quicker methods by using larger safety factors such as over engineering to compensate for assessment risk. Next, although the students who performed this work were near the end of their professional training, they were still not experienced engineers; as such, the duration of certain activities might be longer than those experienced in an industrial situation with more senior personnel.

Finally, this study assumed that the empirical data derived from the full prototype were assumed to be representative of the physical event. The problem with this assumption was that empirical data almost always contain errors [26]. In some cases, higher-end computer simulations may produce better results than those of simply-tested physical prototypes. Only one physical specimen was tested; the testing of multiple samples would allow for the accuracy of the empirical method to be better verified. Future studies should examine alternative components and verification methods as well as address the limitations noted above.

Technology has afforded engineers with a wide array of methods to assess the fitness of their designs. They must choose which assessment method affords them the highest probability of assessment success, while also conforming to time and budgetary constraints. In other words, they must minimize both product and project risk. This study showed an explicit, quantitative relationship between assessment-method accuracy and related engineering effort. This study also incorporated the tendency of project teams to escalate to more accurate methods, when a previous method has produced erroneous results.

It was shown that it can be preferable to choose a more accurate method even if it has a higher cost and lead time. The inability to escalate to a more accurate method later, and still meet time and budgetary constraints, prescribes choosing those methods initially, assuming that the time and budgetary penalties for them are not too great. This study showed that for assessing the structural fitness of a simple manufactured component that these penalties are in fact not too great. The methods detailed in this work can be used to explicitly and quantitatively analyze the effects assessment methods have on product and project risks.

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