A case study of the development of a design enabler tool to support frame analysis for Wright Metal Products, a US SME

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Abstract: This paper introduces a design tool that provides customised engineering analysis functionalities for a manufacturer of metal frames. This work is motivated by the need for supporting small to medium scale enterprises (SMEs) with affordable computer aided analysis tools. The design process followed by a SME, Wright Metal Products of Simpsonville, SC, primarily depends on special expertise of a few key individuals who design products based on past experience, augmented by trial and error. Recognising that this is an inefficient, time consuming, and expensive way of designing products and evaluating their performance, a specialised, simple, and affordable design enabler for engineering analysis is developed to improve the effectiveness and efficiency of the design process.

Keywords: engineering analysis; design enabler; crate design.


Biographical notes: Madhusudan Kayyar was a Research Assistant at Clemson University from 2006 to 2007 where he worked under the guidance of Drs. Joshua D. Summers and Sherrill Biggers in developing designing enabling support software for local industries. He completed his Master’s thesis work in
1 Introduction

Computer aided design and analysis (CAD/CAE) systems are inseparable components of advanced product development practices and various design activities such as geometric modelling, engineering drafting, and engineering analysis (Clark and Wheelright, 1993). However, due to high costs of commercial CAD/CAE systems (licensing and training), many companies still prefer to follow the craftsmanship paradigm of design and manufacturing, relying on expertise of designers. In particular, in many small and medium size enterprises (SMEs), design decisions and product innovations primarily depend on experience-based reasoning with little or no engineering tools applied. This lack of adoption of design automation tools in SMEs may restrict their ability to both efficiently explore the design space and systematically capture and reuse design knowledge.

Given the major role of SMEs in the world’s economy, it is imperative to enhance existing product realisation processes in SME’s through incorporation of CAD/CAE tools. However, vendors of CAD/CAE tools typically develop their products primarily based on the requirements of larger original equipment manufacturers (OEMs). Therefore, CAD/CAE systems are usually equipped with a full range of functionalities required under peak demand conditions. As can be seen in Figure 1(a), CAD/CAE systems are usually under-utilised, particularly in smaller companies where a smaller sub-set of CAD/CAE functionalities is required.

Consequently, commercial CAD/CAE systems become less affordable for many SMEs due to their high costs of purchasing, training, and maintenance. Ideally, the functionalities of CAD/CAE systems should be adjustable based on fluctuations in demand [Figure 1 (b)], and there are in fact service companies that can provide modelling and analysis support under this scenario. Although this scenario can be realised with the aid of some enabling technologies such as web services, it is not the most reliable approach based on the existing information technology infrastructure particularly at SME’s side. The third scenario is customisation of system functionalities based on the requirements of particular SMEs as depicted in Figure 1(c). This paper focuses on the
third scenario. Particularly, the goal of this research is to demonstrate how a specialised computer aided tool can assist the experienced workforce of Wright Metal Products, a typical SME manufacturing firm in South Carolina, to design better products with emphasis on sound engineering principles and tools without actually having to invest in high-end commercial CAD/CAE software and personnel. This tool is referred to as design enabler throughout this paper. Design enablers can be developed for various stages of the design process and are typically customised based on the design process specific to an organisation. The design enabler tool presented in this paper provides an example for customised tools that can support product realisation process in SME’s with sound engineering principles. This tool particularly supports conceptual design phase by enabling efficient exploration of design space and reducing physical prototyping requirements.

Figure 1 Differences between CAD functionality and needed functionality of SME’s, (a) system functionality fixed based on peak demand conditions for hypothetical OEM (b) system functionality adjusted based on demand (c) system functionality is fixed based on the requirements of a particular company (see online version for colours)

Development of design enablers is beneficial for SMEs for several reasons:
1 design enablers are more affordable as compared to commercial CAD/CAE tools
2 they allow designers to maintain their control over the details of the design
3 they can be improved incrementally to better serve their intended purpose.
To develop a design enabler tool, it is first necessary to obtain a sound understanding of the engineering requirements of the target SME. To this end, a specific SME is studied in this research. Based on the results of this study, a new design enabler is developed to support engineering analysis which is a key aspect of the design process. This design enabler tool is designed to support the current workforce with minimal amount of engineering expertise required. This paper provides a simplified description of the technical attributes of the developed design enabler tool (as an example) and mainly focuses on existing gap in SMEs in terms of engineering analysis capabilities through a case study.

2 Case study in engineering design

There are three primary research method tools used in studying engineering design: controlled user studies, protocol analyses, and case studies. Controlled user studies are experimental investigations that are used to compare different design methods and tools under varying conditions, such as comparing progressive idea generation tools with respect to quality, quantity, novelty, and variety, or to provide parameter tuning for different method variables, such as the role that the mode of communication has on design review effectiveness (Ostergaard et al., 2005). User studies have been used to explore analogies in engineering design (Linsey et al., 2005), size factors in morphological charts (Smith et al., 2010) and prototyping in conceptual design (Yang, 2005). Typically, these studies are investigating a single or small set of engineering design activities and are using replication logic to provide statistical grounding for the inferences drawn from the experimental results. In this manner, controlled user studies are interested most in viewing engineering design activities as black-box operands where variables can be adjusted to provide different output responses. Protocol analysis, however, tend to be more interested in the internal operations of the operands. These studies range from non-intrusive with observational data recordings (Eckersley, 1988) to intrusive think-aloud and experimenter-interviewer approaches (Ennis and Gyeszly, 1991). Typically, within protocol analysis, the lower level activities are the data of interest and are extracted through pattern finding in transcripts that are recoded using predefined protocols. Protocol analysis does not use replication logic against multiple participants to build the inference set, but rather uses general trends to extract behaviour patterns for a larger scale engineering design activity than what is investigated using controlled user studies. Both user studies and protocol analysis are done within a controlled environment in which the participants are addressing a predefined problem, in a structured manner, and for a specified period of time. Case studies, however, are used to investigate a contemporary phenomenon with respect to the ‘real world’ context of the case and the associated dynamics of the case (Frost, 1999; George and Bennett, 2005; Teegavarapu and Summers, 2008). In this manner, case studies can be exploratory and used to define new research questions and hypotheses, descriptive to define the specific roles and activities of different participants throughout a design process, or explanatory to provide reasons behind a specific phenomenon (Teegavarapu, 2009).

Four distinct challenges to the validity of use of case studies in engineering design research have been identified: generalisability, lack of rigor, long-time span, and potential
A case study of the development of a design enabler tool

for bias (Teegavarapu and Summers, 2008). As case study research is not based on sample or replication logic, the goal is to derive analytic not statistical generalisation (Yin, 2003). The type of case that is selected for study is critical to determining how much confidence can be placed in the analytical inferences drawn and to what extend these inferences can be applied. Moreover, when case studies are used for hypothesis testing, a single case can be used to disprove a hypothesis (George and Bennett, 2005). The second challenge to using case study research is that it may lack rigor. This concern is a result not of the method itself, but of the history of the method use. There are case study guidelines and best practice that specify how to construct and execute case studies. When following these, a research can self-impose a level of rigor that can mitigate this complaint, collecting and disseminating all relevant data and analysis such that others can examine the findings externally. The third issue associated with case study research, it is typically related to the long-time frame that is taken to implement and conduct a case study. Often times, as case studies are not controlled and are found in the ‘real world’ environment, conducting a live case study means following the design project from inception to completion. This may span months or it may span years. This is a challenge in research, especially in academic environments with graduate students conducting the case studies with uncertain time frames. Finally, there exists a potential for bias reporting case study research. As researchers are looking for specific trends and patterns, it is tempting for them to selectively use and report on data that supports their sought patterns and hypotheses. It should be noted that all research methods, including the traditionally accepted scientific method, involve some degree of subjectivity (McComas, 1998). For this reason, case study research employs falsification logic, the explicit attempt to disprove the researcher’s hypothesis. Moreover, case study research includes triangulation of data findings to ensure that an inference is based on multiple different data elements from different perspectives (Flyvbjerg, 2004). This research employs case study research as an objective method to explore how a design enabler can be developed and deployed in an industrial setting. In this manner, a controlled experiment is not possible and the time frame, spanning multiple months of development and implantation, would not be conducive to a protocol study. All attempts are made to execute this case study in an objective, unbiased manner.

3 Subject of study

The SME, Wright Metal Products located in upstate South Carolina, designs and fabricates metal crates (Figure 2) for transporting and stacking medium size vehicles, such as riding lawnmowers, personal water craft, or all terrain vehicles. Henceforth, the terms crate and frame means the same. Hereafter, Wright Metal Products will be referred to as the company. This case study explores the existing design process followed by the company while designing a product from start to finish. Specifically, the method employed by the current frame designer in developing new products is described. This process is documented based on interviews and surveys with the management, engineering, and production teams. From this, a set of limitations are identified as potential areas of opportunity to augment the current process with new design enablers.
The company employs 45 people in frame fabrication, has two mid-level managers, and one higher-level manager. Currently, the frame design is not done by engineers but by a pair of people who have worked for more than 20 years in the frame fabrication industry and are essentially frame fabricators. The designers have no formal engineering training and do not explicitly employ any engineering analysis or design tools.

A questionnaire was used to obtain information on previous frame designs covering how the customer requirements were collected and documented and the basis for decisions taken while designing, prototyping, and testing a frame. The questionnaire was
design such that information was gathered from two different perspectives: the plant manager and the two shop floor designers. This form of triangulation is critical for case study research. Furthermore, an interview with the frame fabricator was conducted to obtain first hand understanding on the process followed in designing a product from scratch without the use of any design tools.

4 Design process

This section provides a brief description of the existing design process followed by a critique of the existing situation in order to identify areas of potential improvement and enhancement.

4.1 Current design process

The design process at the company follows the general stages of product development (Pahl and Beitz, 1996; Ulrich and Eppinger, 2004) including:

1. identifying customer needs and establishing product specifications
2. concept generation and selection
3. prototyping and testing
4. detail design
5. manufacturing.

Table 1 summarises the design process followed by the company. Also, it highlights the possible tools that could be used at each stage.

The process starts by establishing customer requirements, when, in most cases, the customer supplies an actual vehicle for which the frame is to be designed rather than drawings or CAD models. The customer provides additional relevant documentation, such as the loading and unloading processes and mode of transportation (rail, highway, and ship). The next step is to determine the outside dimensions of the crate based on the size of the vehicle. The optimal design will minimise the envelope dimensions of the crate; a crucial element in determining the number of vehicles that can be shipped in a single container, thereby determining the shipping costs. Once the envelope is determined, the designer proceeds by designing the base of the crate. The main functions of the base include permitting ease of loading and unloading, providing forklift access, preventing improper forklift usage, allowing stacking, and carrying the load of the vehicle. The initial decisions on cross-section of members, forklift points, and the number of vertical and horizontal members required to support the load of the vehicle without significant deformation are solely driven by experience of frame designers. This leads to some trial and error experimentation. However, if the customer provides the currently used frame design, the designers can commence with this as a better baseline.

Preliminary testing is done by placing the vehicle on the fabricated base and then lifting the system with a forklift. No virtual testing is done – only fabricated physical testing. The frame is then visually inspected for any bending or stability issues, thus, forming the rationale for including additional members and/or changing tube gauges. No
significant measurements are taken as the designers simply look at deflections to estimate the severity. There are no engineering tools used at this important stage of frame design. More significantly, the visual inspection is considered an ‘art’ internal to the company accomplished by one of two designers.

Table 1 Design process of the company

<table>
<thead>
<tr>
<th>Task</th>
<th>Time taken</th>
<th>Design tool that could be used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer inputs/order:</td>
<td>Two days</td>
<td>• The requirements list</td>
</tr>
<tr>
<td>• Preparing requirements list</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Converting customer specifications to ‘design specification’</td>
<td>Five days</td>
<td>• Virtual prototyping of concept evaluation matrix</td>
</tr>
<tr>
<td>Concept generation:</td>
<td></td>
<td>• Tool for searching principle solutions from design database</td>
</tr>
<tr>
<td>• Identifying baseline – similar designs that has worked in the past</td>
<td></td>
<td>• Engineering simulation tools used to calculate deflection and stress</td>
</tr>
<tr>
<td>• Identifying changes to be made based on new requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Choose frame member cross-sections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Based on past experience, identify locations needing additional structural reinforcement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototyping and testing:</td>
<td>Three days</td>
<td>• Optimisation tools</td>
</tr>
<tr>
<td>• Testing: load the actual vehicle on the frame and lift using a forklift</td>
<td></td>
<td>• Checklists</td>
</tr>
<tr>
<td>• Visually inspect for bending and possible weak members</td>
<td></td>
<td>• Documentation of best practices and lessons learnt</td>
</tr>
<tr>
<td>• Weld in additional members/change cross-sections/gauges based on preliminary testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Build three to five different prototypes and select the best for production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detail design, manufacturing frame, jigs and fixtures:</td>
<td>Two days</td>
<td>• Decision matrix</td>
</tr>
<tr>
<td>• Build a 3D model of the frame using solid works with BOM and manufacturing details</td>
<td></td>
<td>• Rules and guidelines for manufacturing</td>
</tr>
<tr>
<td>• Weld a set of members separately (sub-assemblies)</td>
<td></td>
<td>• Design report</td>
</tr>
<tr>
<td>• Weld these sets to obtain the final assembly (finished product)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Formal testing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Depending on the layout of the customer’s warehouse, crates may be stacked up to six units high. This puts additional loading requirements on the crates. Therefore, the size of the main members is chosen based on experience such that they do not buckle when stacked in the warehouse or during transportation. This experience is not stored in any failure reports or life cycle documents, but once again as designer experience.
Following these decisions, as many as five different prototype crates are built. The management then chooses a final design based on examination of the design features and how well the frame satisfies the requirements. The chosen design is then subjected to a series of formal tests. If results of tests are acceptable, the design is documented in 2D through AutoCAD. It is at this stage that the product costing is done and quoted to the customer. If the customer chooses to purchase crates from the company, welding jigs are constructed for ease of manufacturing. A significant amount of physical resources have been invested in developing performance prototypes in order to yield customer price quotes.

Based on these formal tests, the company measures how the product meets the customer specifications. However, the company does not know the stress levels in the members, whether the frame is optimised, what the factor of safety is and whether the current arrangement is the most optimum arrangement of members to carry the load.

4.2 Problems with current design process

The failure modes effects analysis (FMEA) chart shown in Table 2 illustrates how attributes from current practices that may lead to failure in design. When designing a new frame, the designer selects a similar, previously successful, baseline design. While this may be a good way to begin in the absence of goodness metrics based on sound engineering principles, the risk with such an approach is that there is no way of knowing how optimal the earlier design was. The crate might have been over designed, and thus overly costly. There may be more efficient configurations of the crate that serve the purpose with less material cost and reduced weight. A simple design analysis tool can help designers start with an existing configuration that is closer to the optimal design.

The other important step in designing a frame is choosing the member cross-sections for the initial prototype. The company stocks different cross-sectional sizes of round, rectangular, or square tubes of various gauges. The decision of what material and cross-section is to be used is based solely on the fabricator’s experience. At the preliminary stage, a cost/strength/cross-section matrix on each of the materials used for crate construction could assist the designer in making an informed decision based on engineering principles rather than experience. However, this may not be required if the company starts using an optimisation tool which would give the cross-sections appropriate for a specific frame configuration.

Currently, there is no way of knowing how good or bad the design is. Furthermore, the tests and visual inspection of the fabricated crate do not reveal much as to the stresses and deflection in each member. If the design is not satisfactory, increasing the gauge thickness of the tube is the most common approach. Increasing the gauge thickness no doubt increases the stiffness and reduces deflection, but may not be the best way to design frame structures. As a result, the company may have a frame that works but is highly over designed, costly, and heavy. The method of choosing a design-based solely on visual inspection is not optimal. Significant valuable assets including time and money are committed in prototype construction before the project contract has been secured. Incorporating the comparison of various design engineering data will aid in arriving at better designs both quicker and with reduced committed resources. Further, since cost analysis is not yet conducted at this stage, it is not possible to evaluate through cost comparisons based on material or manufacturing.
<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>System/component/ function</th>
<th>Potential failure mode</th>
<th>Potential effects of failure</th>
<th>Severity</th>
<th>Cause of failure</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Incorrect customer inputs</td>
<td>Crate that does not meet customer specs, under/over designed</td>
<td>Redesign from scratch, loss of time, money due to re-work, loss of order.</td>
<td>High</td>
<td>No checklists</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>Starting with an existing baseline</td>
<td>Non-optimised solution, expensive design</td>
<td>Unexplored design space, over/under designed, re-work.</td>
<td>Medium</td>
<td>Lack of engineering knowledge-based design, decision-based solely on experience.</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Material selection and sizing of structural members</td>
<td>Improper material/cross-section for preliminary designs</td>
<td>Additional members to be added to counter low strength structure increased weight, cost, numbers of prototypes, trial and error.</td>
<td>High</td>
<td>No available method for comparing solutions, experience-based selection, not able to check stiffness before starting to build prototypes.</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>Preliminary design</td>
<td>Arriving at an inefficient design</td>
<td>Increased number of prototypes, failure to exploit the complete design space, management unaware of the best solution, increased time and cost.</td>
<td>High</td>
<td>Design solely based on experience. Trial and error method of arriving at a solution. No engineering analysis done to verify the design.</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>Designers</td>
<td>Retirement/quitting</td>
<td>Experience is lost. The next designer may not know the thumb rules used by the previous designer. Increased time for designing a new frame. Costly mistakes.</td>
<td>High</td>
<td>Current system of design depends solely on the experience of a few designers, no data/documentation of the thumb rules exist, non-systematic design, no documented design rules.</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>
A design tool to enable frame designers would be beneficial at this stage, allowing designers to explore different alternatives without prototyping and testing each idea. The analysis could also provide important information like deflection and stress levels under load. The strength analysis tool could also be used to generate a preliminary bill of materials by outputting the used members’ cross-sections and lengths. Preliminary cost estimates could be done at this stage and an approximate total cost could be calculated by incorporating different factors to account for manufacturing and assembly. Having the costs presented with each concept would allow the company to look at cost-benefit analysis by comparing features. The tool would allow management to make more informed decisions to select a crate for detailed design and mass production. Table 3 shows the requirements and their importance for a design enable tool for the company.

Table 3 Requirement list for the design enable tool

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Design phase</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creating requirements list</td>
<td>Requirement planning</td>
<td>Systematic creation of design specifications</td>
</tr>
<tr>
<td>Selecting frame configuration</td>
<td>Conceptual design</td>
<td>Quick generation of design concepts</td>
</tr>
<tr>
<td>Selecting member cross-section</td>
<td>Conceptual design</td>
<td>Quick generation of design concepts</td>
</tr>
<tr>
<td>Preliminary cost estimation</td>
<td>Conceptual design</td>
<td>Quick evaluation of design concepts</td>
</tr>
<tr>
<td>Generating preliminary bill of material</td>
<td>Conceptual design</td>
<td>Systematic cost estimation</td>
</tr>
<tr>
<td>Stress and deflection analysis</td>
<td>Conceptual design</td>
<td>Quick evaluation of design concepts</td>
</tr>
<tr>
<td>Design optimisation</td>
<td>Detail design</td>
<td>Systematic design improvement</td>
</tr>
</tbody>
</table>

5 The design enabler tool

Most commercial CAD/CAE packages would be able to perform the above tasks, but the company would incur additional costs of having a specialised personnel coupled with associated licensing costs. Furthermore, many SMEs may not use much of the functionality that commercial CAD/CAE packages offer. While there are some licensing options to free functionality, this company expressed a preference to have a customised tool that to assist the designers at specified design stages.

This case study forms the basis of building a design enabler to assist designers at various design stages. Design enablers can be loosely defined as tools, both computational and non-automated, that are used in the design process in order to enable design engineers in the product realisation process (Summers et al., 2008). These tools can range from problem definition tools such as quality functional deployment (QFD) (Cohen, 1995) and product definition specifications (PDS) (Ulrich and Eppinger, 2004) to idea generation tools such as collaborative sketching (C-sketch) (Shah et al., 2001), morphological matrix (Zwicky, 1969), TRIZ (Altshuller, 1999) and from reverse engineering such as subtract and operate to optimisation such as analytic target cascading (ATC) (Kim et al., 2002).
The design enabler (henceforth, referred to as the tool) presented here incorporates the recommendations from the case study of the company’s process. The design enabler tool shown in Figure 3 is specific to the company.

**Figure 3** Design enabler

![Diagram of design enabler](image)

The tool has been built for frame designers without formal engineering education. The frame designer need not know the intricacies of engineering principles that the tool employs, such as finite element and matrix method of frame analysis. The tool’s purpose is not to completely automate the frame design process nor eliminate the frame designer, but to equip the designer with simple tools to compute stresses and deflection in the frame and optimise the frame members. First, a pre-processing module allows the user to input structural parameters defining initial frame configurations via joint coordinates, member connectivity, loads, and fixity conditions. Then, the computer programme computes a stiffness matrix, load vector, and solves a set of linear simultaneous equations for unknown displacements. The post-processing module then computes member end actions/forces, support reactions, stresses, and writes all of the above results into output text files. The graphics module then plots a 2D top view of the frame with a complete bill of material used in the frame. Significantly, the tool indicates failure or non-failure of the configuration for the given loads.
5.1 Frame analysis

The following steps describe the process through which the tool performs stress and deflection analysis:

1. **Recording structural data**: The user inputs information pertaining to the structure being analysed through keying in the structural data as listed below. The nomenclature used in the computer programme is shown beside the structural parameters.
   a. number of joints (NJ)
   b. number of members (M)
   c. locations of the joints (x, y and z coordinates)
   d. member connectivity information
   e. section properties for each member
   f. the joints to be restrained (NRJ) and conditions of restraint.

2. **Construction of stiffness matrix**: The stiffness matrix is computed by summing contributions from individual member stiffness matrices (Weaver and Gere, 1990). The stiffness matrix is a property of the structure and is independent of loading on the structure. The programme uses the data input to compute and assemble the joint stiffness matrix. The two main conditions for which a frame is analysed are:
   - the frame placed on ground and loaded with a vehicle
   - the frame along with the vehicle is lifted.

Both of these load cases can be approximated as static analysis with the system in equilibrium.

3. **Assembly of load data**: All loads acting on the structure are specified. The user inputs the number of loaded joints. The user then inputs six components of load, three forces along global x, y, and z axis and three moments about the same axis for each loaded joint. This is recorded and assembled into a global force vector by the computer programme.

4. **Solution phase**: A set of $n$ simultaneous linear algebraic equations for $n$ unknowns (free displacements) is solved. The equations are assembled in matrices and solved.

5. **Post-processing**: Using the displacements, stiffness matrix, and rotation matrices, the tool calculates the support reactions and member end actions and the forces at various sections of the members. Stresses are computed with calculated section forces and cross-section properties. The displacements computed in Step 4 and the stresses computed in Step 5 are used to evaluate different frame configurations, highlight failure locations, and determining a factor of safety for the frame.

5.2 Implementation

The matrix method of space frame analysis was coded using VC++ and a graphics module was developed using OpenGL. A Microsoft Excel worksheet serves as the tube database, including various tube parameters and calculated moment of areas that is an
input to the tool. A simple database platform, such as Excel, facilitates data management and reduces complexities of connecting the codes to the database while also being readily available at the company. The designer is able to input a frame configuration based on experience to obtain the stress, deflections, and a graphical display of the concept frame configuration along with the bill of material, max stress, and deflection. The required information includes the number of members, joints, restricted joints, and loaded joints. The tool is intentionally developed as a dialogue-oriented application as a simple interface to allow for non-engineers not familiar with the underlying complexities of the programme to interface with the tool. Figure 4 and Figure 5 show two main tool interfaces for inserting initial configuration of the frame and the coordinates of the joints. Separate interfaces are implemented for inserting loading and member connectivity data.

Once the structure is submitted for analysis, the tool calculates performance and outputs deflection, member end actions, and support reactions to text files. The graphics module plots a 2D drawing of the frame with bill of material as shown in Figure 6.

**Figure 4** The user interface for inserting initial frame configuration (see online version for colours)

**Figure 5** Joint coordinate entry interface (see online version for colours)
While designing a frame using the tool, if the designer comes across a deflection higher than the prescribed value, the designer can reiterate the frame configuration steps and re-analyse the design to ensure that the deflections are within safe limits. The tool is suitable for determining global deflection and stiffness but will not aid the designer in modelling stiffness/deflection of local connections, and other detailed features. Stress results are also global in nature and may have limited use in modelling specific features like the female cup and male boss. Hence, the tool should be used at the conceptual stage of the frame design in arriving at a preliminary frame configuration and determining the cross-sections of individual frame members.

5.3 Verification and evaluation

To verify the results obtained by the tool, the calculated outputs were compared against the result obtained by ANSYS, a commercial CAE system. The frame shown in Figure 7 was analysed using the design enabler tool and ANSYS. In this frame, joints 1 and 2 are fixed in all degrees of freedom. Loads are prescribed on joints 6, 7 and 8. The values of load, the joint number, member number and cross-section numbers are shown in Figure 7.

The results are shown in Table 4.

Ux, Uy and Uz are the displacements in X, Y and Z direction. As can be seen in this table, the displacements computed using the tool and ANSYS are the same to 4 significant figures. In order to validate the tool more rigorously, a displacement comparison based on some of the more complicated ANSYS element types (such as beam elements for the horizontal members) and more realistic loading conditions (such as a horizontally applied load) are required.
**Figure 7** Frame configuration used to test the tool (see online version for colours)

**Table 4** Comparison of displacements calculated from the design enabler and ANSYS

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>Displacement</th>
<th>Design enabler tool</th>
<th>ANSYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Ux</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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To evaluate the performance of the tool, a four-hour training session was conducted to demonstrate the tool at the company and then frame designers in the company were asked to use the tool during frame design process. Responses to the tool were positive, though adoption of the tool has been stronger through the sales team’s use in offering real-time cost estimates for frame orders. The fact that sales personnel can use the tool without any difficulty supports that the simplicity requirements for the tool are successfully met.

6 Summary

This paper introduced an SME case study and a resulting design enabler providing customised engineering analysis services. Supporting the designers with a simple, yet effective, design enabler that allows them to quickly evaluate design alternatives is the major motivation for this work. In particular, this research addresses the needs of the WMP whose designers have no formal engineering training. Given the significant contribution of SMEs in US economy, it is critical to enhance the engineering capabilities of this sector in a cost-effective manner. Thus, this case study can be considered as an initial template in how to successfully collaborate with SME’s in the development of future design enablers.

A metal crate design and manufacturing company was selected as the subject of study. The design process of the company was studied in order to identify the areas in which design automation serves beneficial. From this study, it is observed that the company’s current product design process relies heavily on past experiences of select workers within the company. Improving the design process requires integration of systematic design procedures and the creation of an interface in the form of design enablers to incorporate engineering knowledge as driving factors in crate design. To this end, a design enabler was developed for deflection and stress analysis leading to a notable reduction in design cycle time that is still currently limited by full scale prototyping and testing. This tool is based on classical matrix structural analysis with limited load and restraint capability designed to simplify the analysis process for designers with limited knowledge of engineering fundamentals. The tool incorporates the recommendations from the case study of the design process followed by the company. The role of the design enabler developed in this work is to assist the designer at the conceptual design phase and not to eliminate the human designer or completely automate the design process. The tool could save time in terms of prototyping, testing, but is currently being primarily used for sales as the current corporate culture is still resistant to trusting computer analysis.

Initial implementation revealed that with the aid of the engineering analysis module, the designer is able to analyse a particular crate configuration in matter of few hours as compared to few weeks in building and testing a crate prototype, and then making suitable changes to arrive at a concept design of a crate. However, the company, aside from the high-level management, does not seem to be receptive to trusting computation analysis, citing instead that the experience of the designers is invaluable. Unfortunately, after introduction of the tool, originally intended to help mitigate the potential loss of expertise enshrined in the two expert designers, the high-level management was replaced by a mid-level manager that was openly resistant to computer tools in deference to physical testing and prototyping.
There exist several areas for future enhancement. One possible extension is to generate the 2D drawing of the crate through a CAD software. Currently, the user needs to key in the numerical data such as, the joint coordinates and the member connectivity which is time consuming and error prone. Also, structural topology and shape optimisation algorithms can be included in this tool. Other extensions include incorporation of rule-base and case-based reasoning modules (Kolodner, 1993) in the tool.

References


A case study of the development of a design enabler tool


Notes

1 Product of Autodesk (http://usa.autodesk.com).