AC 2009-2150: APPLYING AXIOMATIC DESIGN AND KNOWLEDGE-BASED ENGINEERING TO PLASTIC DRUM DESIGN

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Abstract

Over the past three decades the concept of design and development had evolved and changed a lot with the raising level of science and technology and also with the impact of globalization. Many organizations, small and large have a traditional design and development concept, where a product is designed from its conceptual stage and working on a long term plans for the product. The impact of globalization on business has forced most industries to become more innovative and implement newer strategies to retain market leadership and growth with the desired profitability. The retention of corporate engineering knowledge and rules is also critical because of the aging workforce. Engineering and design move hand in hand, they are both synonymous and synchronous. Engineering design is one of the most intellectual challenges in the fast changing world. The concept of Knowledge Based Engineering and Axiomatic design is used as the means of being competitive in the industry by meeting all the functional requirements of what a customer needs in a product. Axiomatic design is used to show that the design is done using fundamental sets of principles which would make an efficient design and use of Knowledge Based engineering is a concept that would allow the retention of corporate knowledge as initiate-level engineers and designers enter the workforce. In this paper, authors discuss about the two concepts which involves designing a plastic drum that is used to store lubricants.

Introduction

This paper examines a product that is currently in development at Greif, Inc., Mount Sterling, Kentucky. The traditional design process was not applied to this design for several reasons. The traditional design process is time consuming and resource intensive. It accounts for 75% - 80% of a product's life cycle4. The time that is wasted can be used for value adding phases of a product's life cycle. The traditional design process should be replaced for a more efficient process. This paper will exam two such design processes. The first process is knowledge based engineering (KBE). KBE has applications in design (CAD), analysis (FEA), simulation (CAS), optimization, manufacturing, and support (CAPP). These applications allow for hands off designing and design automation. The second process is axiomatic design. Axiomatic design relates a new design to the Independence Axiom (Axiom 1) and also to the Information Axiom (Axiom 2). The process begins by stating any customer requirements (this happens in the customer domain). The customer's needs are then translated into the functional domain. The functional domain is where various functional requirements (FRs) are defined. Design parameters (DPs) are conceived in the physical domain. All the domains are then related to the process domain. The process domain is where process variables (PVs) are conceived based on manufacturing data. Both the methodology is explained using an example of a twenty three (23) gallon grain storage drum. The 23 gallon drum is designed to be an integrated packaging system for grain feed for the cattle industry. It will feature a pallet-less design to reduce the customer's cost of buying and storing wooden pallets. The drum is designed so that four drums would create a forklift channel similar to that of a wooden pallet. The forklift channels are offset one inch from the centerline of the drum so that while lifted the drums would lean inward. The inward lean would allow the drums to lean on another and provide stability. The drums are designed to be nestable within one another while not in use. This feature was added so that the space needed to store the drums would be reduced thus saving the customer storage costs. The drum's geometry is tapered to allow for the nestability. The circular geometry at the bottom of the drum provides the user with option of rolling the drum from place to place. This feature allow for ergonomic design because the user would not have to lift a drum that is filled to 250 pounds. The triangular extended and recessed panels allow the drums to be stacked on top of each other while being transported. The drum's top dimensions were restricted to less than 24" so that an extra set of drums could fit on a truck and save the customer shipping costs.

Knowledge based engineering (KBE)

KBE originated from a combination of CAD and knowledge based systems. KBE combines past design methodologies and rules with manufacturing process knowledge to create an optimized design[5]. A combination of CAD and KBE allows for automation inside the design environment. When using a CAD-KBE, design for manufacture can be gained by applying materials and process variables to the design. Knowledge based systems organizes the design knowledge so that it can be useful in the design environment.

Application of KBE to plastic drum design

The knowledge based approach to plastic drum production uses a KBE and CAD relationship. When both tools are utilized together, an effective design can be produced. The steps to utilizing both KBE and CAD effectively are stated in Figure 1.

The initial step in any design process is to identify the customers' requirements for a new product. . In this particular example, the customer(s) requested a pallet-less, 23 gallon grain storage drum. This design required that sets of four to eight drums be shipped together, but at the same time eliminating the use of a pallet. The drums would also need to be stackable. To eliminate the use of pallets, the drums would feature forklift channels at the base.

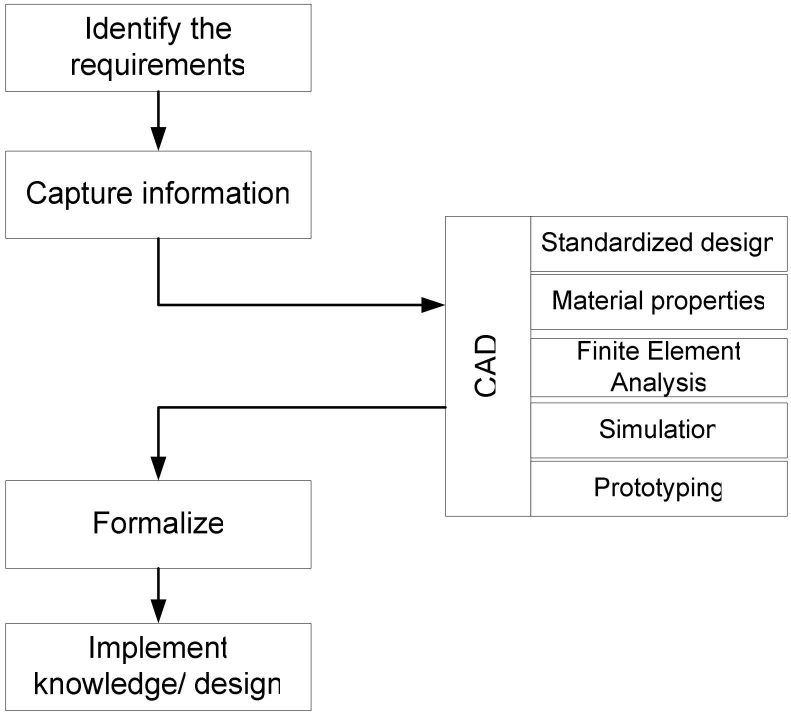

Figure 1: KBE and CAD Relation[1]

For the informational requirement of the design, the new drum will use design data from the company's original 23 gallon storage drum. The original drum featured a rounded base with a multisided top. For the new design, the drum will retain the rounded bottom of the original design and will feature an eight side top. The new design will use a modified CAD model of the original drum.

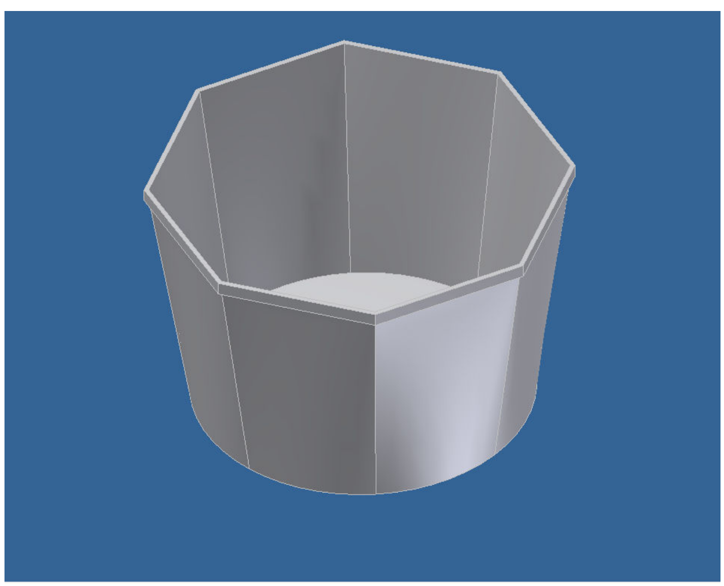

Figure 2: Modified Version of the Original Design[1]

The third phase is to standardize the design. The original drum is an industry standard design. Since the new drum uses design information from the original design, it is also a standardized design.

The next step is to design the product using CAD software. Autodesk® Inventor was used to design the new storage drum. Fillets were automatically added to the drum by specifying the edges and the fillet radii. External drafts were also automated. One draft was added to the drum and the remaining drafts were added by creating a circular pattern about the drum's origin. Stacking tabs were added to the drum using the same process of creating a circular pattern.

For a product to be manufacturable, the product must be designed for manufacturability. Certain aspects of design for manufacture were also automated. A shell feature was used to obtain a uniform wall thickness throughout the drum. A uniform wall thickness allows the molten plastic resin to flow evenly through the mold during injection molding. The draft angles were added by making the drum's top diameter larger than that of the bottom. Draft angles allow for the final product to be removed from the mold. Draft angles also allow for nesting. The fillets that were added earlier also aid in removing the final product from the mold. The fillets also add strength to the drum.

Materials attributes were also added to the CAD model. The material (high density polyethylene) was not contained in Inventor's material database. The styles and standards editor was used to add the material to the database. Adding the correct material to the model aids in FEA and simulation.

FEA was used to determine if the design could handle loads in excess of 250 pounds. The analysis measures material fatigue, contact point stress, and deformation.

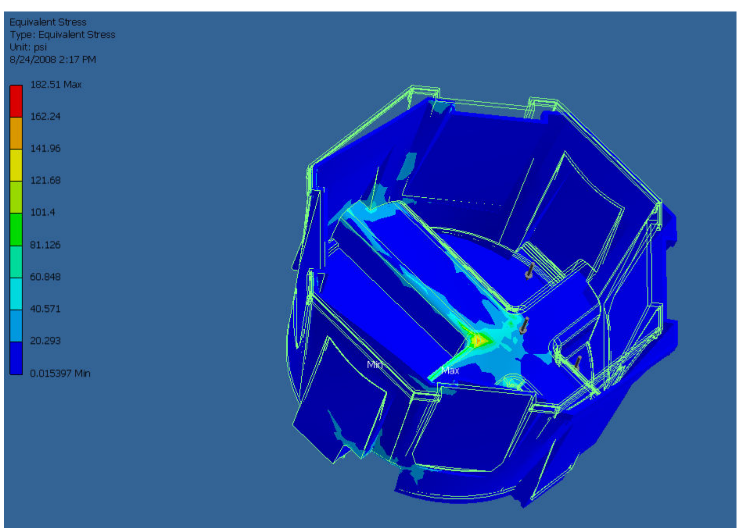

Figure 3: FEA[1]

Simulations were also performed on the CAD model. To begin the simulation, eight drums were assembled together. The simulation was them used to determine how the set of drums would react to stresses caused by a forklift. Based on the results of the simulation, the designers decided to place the forklift channels one inch from the centerline of the drum. Offsetting the channels force the drums to lean toward one another, therefore stabilizing the set of drums. Simulation was also used to determine other aspects of the drum. The connection and locking between the drums were simulated to see if there was any mismatch between the drum while stacking. A simulation video created inside the CAD software was used to show product capabilities to customers.

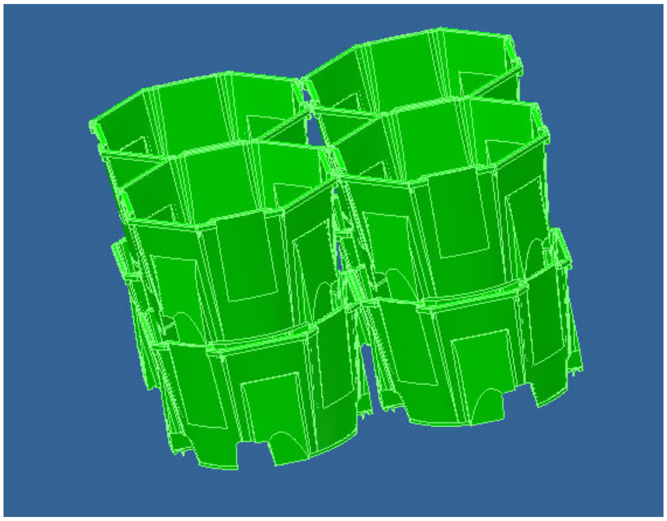

Figure 4: Stacking Simulation[1]

Prototyping was automated using Inventor. The native .ipt file was automatically converted to .stl file that is used by various stereolithographic machines to make prototypes.[1]

Axiomatic design

Axiomatic design is used to design a product based on the independence of the designed functions and the information content contained in the design. The information contained in a knowledge based environment can also be used as the information content in the axiomatic environment.

Customer domain

In the customer domain, the needs of the customer are stated. The designer does not need to think about the functional or physical characteristics of the product during this stage. In this stage it is very important that designers work with potential customers[2]. It is essential that designers work with customers because the customer can clearly state any needs to the designers. It is also that all parties involved with any aspect of the products design be involved in the design cycle[2]. This means that engineers, designers, marketing, shipping, manufacturing etc be involved with the product from the beginning of the lifecycle. This will ensure that the customers' needs are met.

In the case of the example of a plastic drum, the customer required a palletized storage drum. The drum needed to match the capacity of the previous model. The drums needed to be nestable

/ stackable inside one another. One major requirement for the design is that eight drums be shipped together with a layer of fours drums on the bottom and a layer of four drums stacked on the bottom layer. The customer also required a way for the drum to be manually transported.

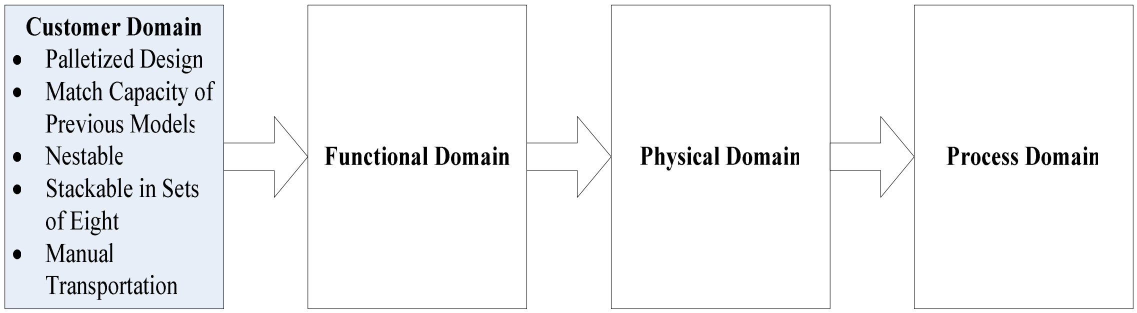

Figure 5: Customer Domain

Marketing worked with the designers from the beginning of the drum's lifecycle. Marketing related the customer requirements to the designers. The designers then used the customers' requirements to create the data in the customer domain.

Functional domain

The functional domain is where customer requirements are translated into FRs and the design objectives are stated.   FR's is the minimum set of requirements that characterizes the design's functions[2]. The Independence Axiom must be satisfied in the functional domain. FRs are a description of the designers' goals.[2] In the functional domain a design that can accommodate a large amount of variation on DPs and PVs and still satisfy the design goals functionally is desired.[2] Any design that can satisfy FRs, DPs, and PVs is a robust design.

The example product must be able to handle loads in excess of 250 pounds. The drum will also need to have a capacity of 23 gallons. To accommodate a palletized design, the drum will feature channels along the base of the drum (the channels will enable forklift forks to slide underneath the drum). Drafts will be added to enable drum nesting. Extended panels will be added to both the inside and outside of the drum to allow stacking. The drum will also feature handles. The side walls need to have limited flexibility.

$$FR_1 = handle\ loads\ over\ 250\ pounds$$
$$FR_2 = 23\ gallon\ capacity$$
$$FR_3 = forklift\ channels$$
$$FR_4 = drafts$$
$$FR_5 = internal\ and\ external\ extended\ panels$$
$$FR_6 = handles$$
$$FR_7 = limited\ side\ wall\ flexibility$$

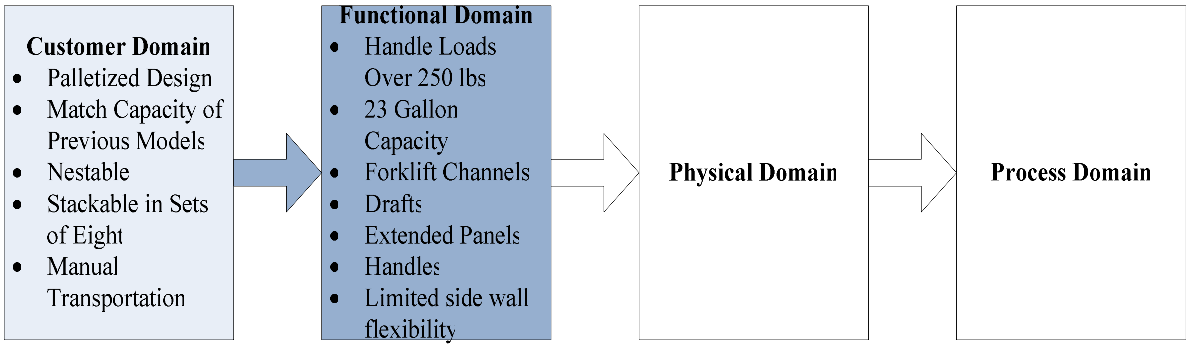

Figure 6: Functional Domain

Physical domain

DPs are created in the physical domain. The DPs are related and mapped to the functional domain and each FR. In the physical domain, the designer begins to think about the appearance of the design and how each FR will appear on the product. Once DPs are conceived and mapped back to the physical domain, the product is designed[2]. The DPs can be created by using past, proven design knowledge.

To accommodate loads of over 250 pounds, the drum will feature ribs along the walls of the drum. A height of 15 inches will be used to create a capacity of 23 gallons. The height was carried over from a previous design. The forklift channels will be positioned one from the centerline of the drum. The channels will be located on the base of the drum. These two attributes will allow a standard size forklift to be able to lift a set of drums. To achieve a draft angle on the drum, the top of the drum will have a larger diameter than the base. Also to achieve a larger amount of draft, the top of drum will feature eight sides and the base will be circular. There will four internal extended panels located on four of the top sides. There will also be four external extended panels located on the base of the drum. Both sets of panels will taper into the side wall of the drum. The panels will be oriented so that the external panels of one drum will be able to rest on the internal panels of another drum. Handles will be created by adding a lip to the top of the drum. The ribs for stability will be located inside this lip. Limited side wall flexibility will be achieved by adding large radii to all sharp edges of the drum. The radii will add strength to the walls.

$$DP_1 = ribs$$
$$DP_2 = 15\ inch\ height$$
$$DP_3 = forklift\ channels\ located\ one\ inch\ from\ the\ centerline$$
$$DP_4 = larger\ top\ diameter\ than\ the\ bottom\ diameter$$
$$DP_5 = external\ panels\ will\ rest\ on\ the\ internal\ panels\ of\ another\ drum$$
$$DP_6 = lip\ along\ top\ perimeter$$
$$DP_7 = large\ radii\ on\ sharp\ edges$$

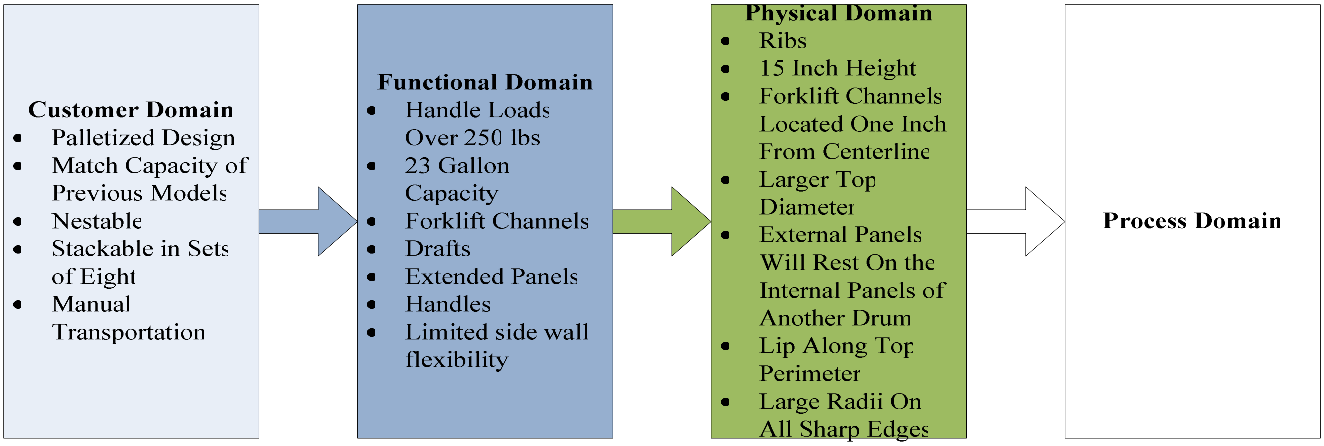

Figure 7: Physical Domain

Now that the DPs have been stated, the product is designed.

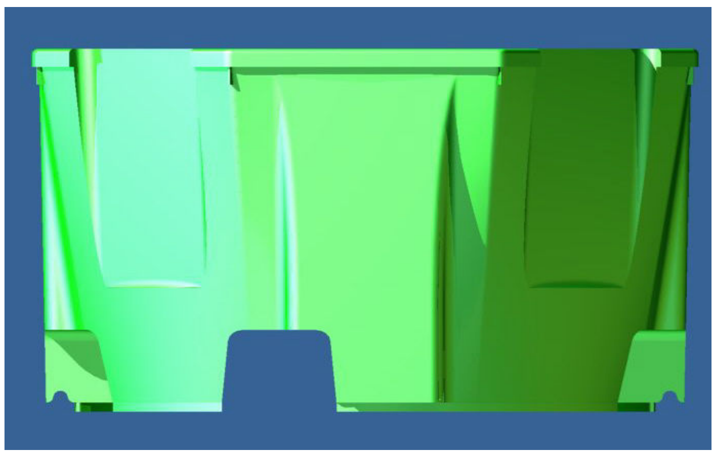

Figure 8: Final Product

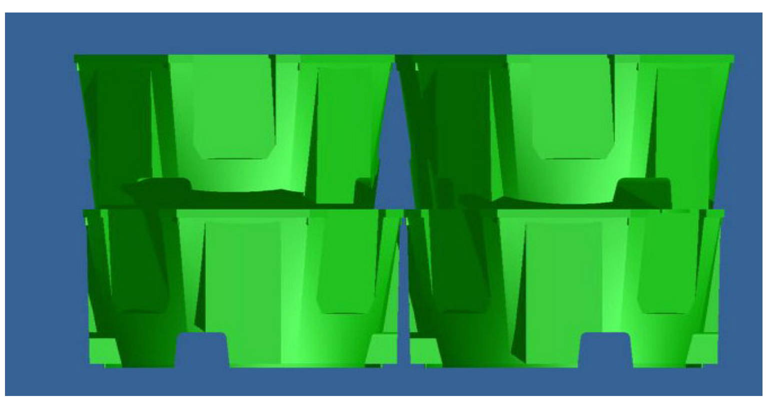

Figure 9: Stacking Ability

Process domain

Now that the product has been designed, process analysis needs to be performed. The product needs to be checked for manufacturability. To achieve minimum costs, the product needs to be manufactured using existing processes. Information for current process can be obtained from a KBE environment through databases of processes. The essential processing information is what affects the fulfillment of the functional requirements. There are many techniques like the Design for Manufacturability that is combined to axiomatic design theory that is used for the design of a product[7].

In the case of the example product, the drum will be manufactured by injection molding high density polyethylene. The design is manufacturable in its current state. The drafts will enable the drum to be pulled off the mold easier. The radii that were added for strength will also enable the drum to be pulled off the mold.

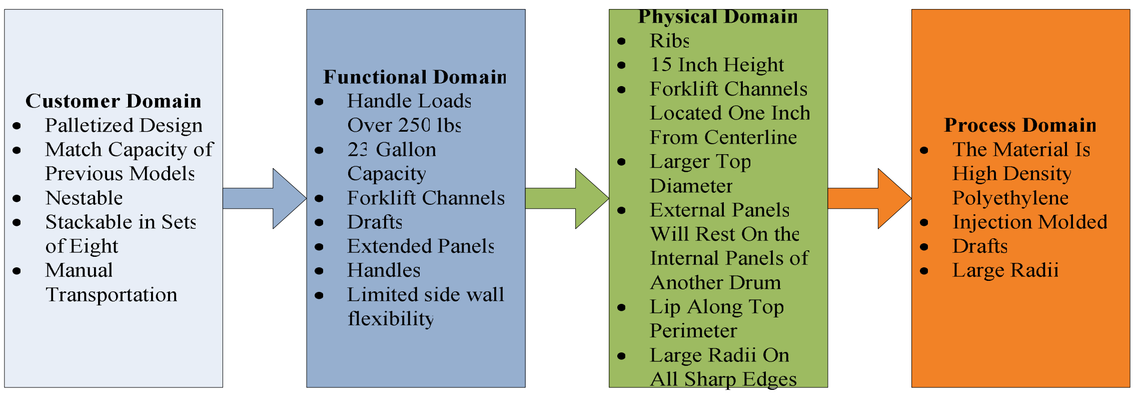

Figure 10: Process Domain

Design analysis

The design will now be analyzed for its acceptance of Axioms 1 and 2 and also for design coupling. Axiom 1 states that FRs must be independent of one another[3]. A design will satisfy Axiom 1 when a specific DP can be changed to agree with its corresponding FR and other FRs are not changed[3]. A design that can satisfy Axiom 1 is the optimum design .[3] In order to verify the independence of each FR, the functional domain needs to be mapped to the physical domain.

$$[FR_1] \rightarrow [DP_1]$$
$$[FR_2] \rightarrow [DP_2]$$
$$[FR_3] \rightarrow [DP_3]$$
$$[FR_4] \rightarrow [DP_4]$$
$$[FR_5] \rightarrow [DP_5]$$
$$[FR_6] \rightarrow [DP_6]$$
$$[FR_7] \rightarrow [DP_7]$$

A design's compliance with Axiom 1 can also be confirmed by using the product's design equation. The design equation consists of the FR vector, the DP vector, and the design matrix.[3]

$$\{FR\} = [A]\{DP\} \quad \textit{Design Equation}$$

The design matrix for the plastic drum is shown below.

$$[A] = \begin{bmatrix} A_{11} \\ A_{21} \\ A_{31} \\ A_{41} \\ A_{51} \\ A_{61} \\ A_{71} \end{bmatrix}$$

Now, substitute the rest of the design equation.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \end{Bmatrix} = \begin{bmatrix} A_{11} \\ A_{21} \\ A_{31} \\ A_{41} \\ A_{51} \\ A_{61} \\ A_{71} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \end{Bmatrix}$$

Confirm that there is functional independent by multiplying the design matrix by the DP vector.

$$\begin{aligned} FR_1 &= A_{11}DP_1 \\ FR_2 &= A_{21}DP_2 \\ FR_3 &= A_{31}DP_1 \\ FR_4 &= A_{41}DP_4 \\ FR_5 &= A_{51}DP_5 \\ FR_6 &= A_{61}DP_6 \\ FR_7 &= A_{71}DP_7 \end{aligned}$$

According to the design equation, each FR is independent of one another; therefore Axiom 1 is satisfied. This design can be classified as uncoupled design. A coupled design is a design in with there is interdependence between FR's. In the plastic drum design, a DP can be changed and the only effect will be seen on the corresponding FR (i.e. an uncoupled design).

After the designer analyzes the design for compliance with Axiom 1, he needs to also analyze the design for compliance with Axiom 2. Axiom 2 states that the information content of the design needs to be minimized[2]. The design needs to be an uncoupled design with a minimal amount of information. An optimal design will have an equal number of FR's as it does DPs. Again, past design knowledge can supply the information for the design.

The example design satisfies Axiom 2 because the number of FRs and DPs are equal. It also satisfies Axiom 2 because there is a minimum amount of FRs in the design. There are currently seven FR's. The number cannot be reduced any further without compromising the functioning of the design.

There are various corollaries pertaining to axiomatic design. One such corollary states that the designer should use symmetry (as long as the design is remains an uncoupled design) [2]. The plastic drum makes uses of symmetry of shape. Every DP is centered on the origin of the drum. The drum also is consistent with the corollary stating that the designer should design a product with the least amount of information and that is uncoupled. As proven earlier, the drum design accepts this corollary.

Like the corollaries, there are also various theorems that apply to axiomatic design. The first theorem states that coupling will occur if the number of DPs is less than the number of FRs[3]. In the example, the number of FRs is equal to the number of DPs. A similar theorem is if the number of DPs is greater than the number FRs, the design is redundant[3]. An ideal design has an equal number of FRs and DPs. The plastic storage drum is an ideal design because the number of FRs and DPs are equal to one another. The path independency theorem states that the information content of an uncoupled design is independent of the changes to DPs[3]. This means that when one DP is changed, only the corresponding FR will adapt to the changes. All other FRs will remain the same. The example also satisfies this theorem because each DP is only reliant upon its corresponding FR. An example of this is a change in the height of the drum will not affect the top or bottom diameters of the drum.

Conclusion

Axiom design is a systematic approach to design applications. It breaks the design process into four distinct domains (customer domain, feature domain, physical domain, and process domain). Each aspect of the domains is mapped to other domains to analyze the independence and information content of the design. A design that produces the least amount of information and interdependency between function is the ideal design of a given product. The plastic drum is an example of an ideal design. The plastic storage drum is only one application of axiomatic design. Other applications include design of systems and process and also software design. Axiomatic design is so widely used because it saves valuable design time while also producing quality designs. Axiomatic design combined with knowledge based engineering is also useful when designing a new product. KBE can supply the information for the design as well as validating the design by using proven design knowledge. This combination of KBE and axiomatic design shortens lead times and get the product on the market quicker than the traditional design process.

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