Modular Crates:
A Holistic Design Approach for Optimizing Cube Size in Industrial Packaging

ABSTRACT

Global market is a field where all industries strive to provide personalized product for every customer demand in order to compete with their competitors in the business battlefield. Product personalization varies with customer to customer which increases the product variety. When the product size variability is vast, producing packages for every individual product is not only difficult but also increases the design time, production time, total manufacturing cost and inventory cost. For the present scenario, Industrial packages does not opt customizability for variable product sizes. Customized package for personalized product is achievable only by redesigning the existing distribution package with modularity and adaptability functions which helps to reduce space wastage on logistical distribution and warehousing ultimately leading to proper cube utilization. In this paper, by analyzing the production feasibility and manufacturing strategy, new innovative re-engineered industrial package designs with customizability functions are developed and are evaluated by introducing a matrix called Collaborative Design Performance (CDP) Matrix. From the matrix and order penetration point (OPP) analysis, it is evident that the re-engineered designs adopt process commonality and postponement in an effective way.

KEY WORDS

Modular crate, Cube optimization, Collaborative Customization, Distribution packaging, Plywood crates

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INTRODUCTION

Packaging serves as a multidisciplinary function and plays a major role in supply chain. A pack fulfills its purpose only when it satisfies both technical and marketing functions. In many cases, the product manufacturing industries take all the necessary measures to ensure quality and to match their competitors. But they fail to take measures in the right packaging for the product, resulting in product damage during shipment. Engineering and designing a distribution package for a specific product needs all the inputs and foresights of the consequences that the product would face on the way to reach the final consumer.

Proper utilization of area in warehouse and trucks can only be achieved on improving unit load efficiency. In order to achieve maximum efficiency in the whole packaging system, one must start concentrating on the primary package design. As of now, for distributing products across the world, engineered plywood boxes are used. These engineered plywood boxes are also termed as ‘Plywood Crates’, has been an alternative for conventional wooden crates, uses less material with the demanded strength ultimately helps us to maintain environmental sustainability.

Placing the product in-tight to the pack and reducing the space inside & between the pack is termed as cube optimization. Accomplishing it would not only reduce the raw material usage, space wastage and shipping cost but also helps in transiting the goods safely to the customer. Several recent researches [1-3] have formulated a non-linear optimization model, product family architectures, multi-objective optimization method to balance the crate types and wastage space inside crates and optimized with customer preference data.

Modular design

Modularity is achieved by standardising the modules/components and accomplishing the diversity of the product variety to satisfy the basic desired product function on the customer’s demand. Several researchers have proposed various ideas of modularization in various engineering applications. Several recent researches [4-10] designed product architecture for maximizing the overall modularity, accomplished a risk-based design structure matrix which aimed at controlling the future operational risk profile when compared to the actual design, proposed a multidisciplinary design optimization that demonstrates how the design and methodology combination can be applied to large scale industries, multifunctional conceptual design of multimodal products dealing with changing working environment, tasks and requirements, discussed the commonalities found across the provided three models of designing, modeled an multi-skeleton approach to illustrate design process, design change and module reuse in the complex products development, introduced a matrix based technique- Engineering Change Forecast (ECF) matrix to prioritize the components for modularization.

Process commonality and postponement

Process commonality is the common processes or operations in a production flow in order to manufacture diversified product varieties in a product family. Opting process commonality strategy simplify the production planning, increases productivity, improves process flexibility, reduces production cost, set-up time, material cost, inventory carrying cost and lead time on uncertainty. The approaches [9,12] used a multiple product family metrics for establishing an effective platform redesign strategy using commonality and variety metrics, developed a simulation model incorporating process commonality into production system benefits when uncertain situation occurs.
Incorporating process commonality into manufacturing system leads to postponement. Process commonality satisfy the concept of configure to order (CTO), which is a hybrid of make to order and assemble to order strategy. As shown in the Figure 1, a common manufacturing process is carried out for making standard box with customizability function and stocked in inventory. As the customer order is placed, the sub-assemblies respective to the order is produced and assembled with the standard box. Thus by postponing the sub-assembly production with respect to the customer needs, the product variation is possible and diversified by the sub-assemblies made to the demand.

![Fig. 1: Overview of Production flow-Process commonality and Postponement](image)

The recent strategies and models [11,12] presented a conceptual model to improve supply chain flexibility at times of uncertainties by using two strategies which are reactive and proactive that includes commonality and postponement supports with higher flexibility. From another perspective [13,14] analyzed two distinct strategies: production postponement and information sharing to reduce manufacturer’s uncertainty about demand and shows the value of interaction between the two strategies in terms of manufacturer’s and retailer’s perspective. Thus from the study of papers, it is clear that product design facilitating postponement enables rapid customization and proves to be an effective approach to overcome uncertain demand situations.

**Minimum Order Quantity (MOQ)**

Since the production of engineered plywood box can only be done with MOQ, producing plywood boxes for each individual product dimension seems impossible. So the following Table 1 shows how the variants are minimized by the packaging solution industry at present. Usually, 25 mm clearance is given on the length, width and top of the box. A requirement is placed from the valve industry with more product variability and packaging industry further minimized the variants for to make uncomplicated production. As listed in the ‘Dimension with clearance’ column, the dimension of the product varies hugely so these are differentiated by using different colors like orange, blue and green which shows assorted dimensions and thus producing the box for each dimension increases the setting time which ends up in intricate production.

Thus categorizing the dimensions with minimum variation as a batch, listed in the ‘Sorted Dimensions’ with respect to the colors orange (Batch I), green (Batch II), blue (Batch III) helps to produce a common size box for all the variations in a single batch makes the production viable. Service based industries usually make the production maintaining a MOQ. In this case, should not be less than 10 boxes per batch. So, it is clear that the second batch with the dimension of 1200 x 900 x 600 mm has only an order quantity of 7 boxes which does not fit with the MOQ. As a general rule, the dimensions that do not fit with the MOQ are produced to the next possible dimension.

In this case the 7 boxes from the batch II with the dimension of 1200 x 900 x 600 mm conjoin with the batch I with the dimension of 1200 x 1000 x 600 mm, increasing the number of boxes from 14 to 21 in the batch I. Modifying the box size with respect to MOQ would also affect the effective utilization of warehouse and truck space. So, the 7 boxes from the batch II conjoin the first batch in order to maintain the MOQ level, it is clear that 100 mm
space wastage occurs on width side of all the boxes for the batch II. These left out spaces are filled using padding material to resist product movement during shipment. These boxes on container stowage make total space wastage of 700 mm on the width side which remains unoccupied inside the container.

Figure 2 explains the stated problem with an illustration of an inside view of the package on the container during transit. As shown, five different product sizes A, B, C, D, E are packed and distributed. In which the dimension of the box are produced for the product dimension E, as it is the ultimate product size
in the batch. All the other product sizes can be packed onto the ultimate dimension box size, provided the left out spaces are to be filled using padding. The space wastage inside the pack does not only affect the carriage cost but also increases the carbon footprint, from the time of manufacturing to distribution.

**Demand uncertainty**

When a predicted level of demand goes awry due to the changes in customer need, demand uncertainty is created. Figure 3 shows the valve’s schematic diagram, for which the packaging industry manufactures a box. As this extra part is not mentioned in the schematic diagram, the box manufactured does not fit to the product’s final dimension as the box requires an additional space to accompany the extra part. For this uncertain case, the valve industry pulls the required boxes of new dimension from packaging industry. This demand uncertainty caused delays the shipment to be made at the desired time. Since packaging industry follows Engineer to Order (ETO) strategy, it has to manufacture a complete box from the design stage which requires a long lead time to deliver the order to the customer.

Thus for the present situation, designing a standard box with a customizability function to modify the pack for variable product sizes depending on customer requirement would help the packaging industry to overcome the above stated problems. Exercising this modifiable box in real time eliminates the consideration to maintain minimum order level as the standard box on adding plywood sub-assemblies depends on the required dimension that can fit into many size variants. This modular package also enables maximum unit load efficiency on warehousing and during shipping/transit. Since the customizability function is provided, only sub-assemblies have to be produced and delivered at times of demand uncertainty which ultimately reduces the lead time.
MATERIALS

IronCAD design software

IronCAD, a software for modeling 2D and 3D CAD (Computer Aided Design) designs. For modeling the conceptual designs and conventional design, IronCAD 2015-3D Scene were used. Tongue, post, flat post, profile and klimp were modeled by editing the cross-section of an imported block from the catalog browser. The edited shapes were then saved onto the catalog browser, so that the shapes were readily available for future use. The modeled shapes were positioned, assembled and disassembled using Tri-ball function, which also used as an editing tool during design modeling.

Poplar plywood

The scientific name for poplar plywood is ‘populous nigra’, which has good moisture resistance, maximum bending strength and durability. The material was available in various thicknesses ranging from 4 mm to 30 mm. Poplar plywood were procured in sheet form of size 2440 mm x 1220 mm in dimension with 5-15% of moisture content. In order to reduce the package weight, the designs were modelled using lower plywood thickness of 7.5 mm with 5 ply structure. For 5-ply, the direction of the veneer fibre at the core-ply and outer-ply is the same. Thus, the tensile stress and tensile strength would be more for the load applied in parallel to the grain direction.

Steel

Hot dip galvanised steel sheets were used in the design as the sheet combats corrosion even in any harsh environment. It is procured in roll form of thickness 0.8 mm with the tensile strength of 350 – 440 N/mm2 and yield point of 240 – 300 N/mm2. Efficiency of resisting corrosion gets improved with zinc coated hot dip galvanised steel. The coating thickness of zinc on to the steel is 100 – 200 g/m2. It is produced and shipped in coiled sheets with the width of 850 mm.

METHODOLOGY

Engineered plywood boxes work flow- Conventional Design

Engineered plywood boxes are designed to fulfill the functions of distribution package. For industrial packaging application, these boxes are widely used as primary packages. Since it is known that lower the material thickness, lesser would be the shipping cost, the boxes are made using plywood material. Plywood sheets are joined by tongue joints. These tongue joints are used to enclose the box in all sides (long-side, short-side, lid and bottom). Figure 4, shows the disassembled view of the box, where the long-side and short-side edges are attached using tongue-post joint and lid/bottom gets attached using tongue-profile joint. The tongue joints are provided for easy assembling and disassembling of the box and the tongue-post joint is provided to withstand compression and stack load during warehousing and shipment.

Fig. 4: Conventional design- Engineered plywood box
The boxes are produced in such a way that the sides can be collapsed and placed over the pallet during the shipment from packaging industry to the product manufacturing plant, thus reducing the space on warehousing and transportation. In general, the box loading should be done by block stacking method considering the strength of the box is higher at the edges and the products are fixed inside the box in such a way that the weight of the product is distributed to the pallet.

Figure 5 shows the production work flow of a conventional plywood box in which the lid and bottom undergoes the same set of operations and the posts are press joined only to long-side edges, whereas the short-side has only tongues. Production technique for manufacturing the conventional plywood box are discussed as follows,

**Plywood cutting/trimming operation**

Plywood and pinewood was cut and trimmed in Holzmann machine. The bed length could accommodate the plywood size of 2440 x 1220 mm and the maximum work piece thickness of about 200 mm can be cut at a single stroke.

**Chamfering operation**

Once the plywood was made to cut in Holzmann machine to the required size, it was sent to the chamfering process. Chamfer with the angle of 45o was made on the length, width, lid and bottom edges of the box to make better contact between edge surfaces preventing slippage and also helps the tongues to make a proper contact with tongue slots.

**Tongue punching operation**

Tongue was made of galvanized steel with 0.8 mm thickness. On forming the box, two plywood sheets were to be attached and this was done by tongue joints. Tongues were formed by die-cut which included lancing and punching operation. By lancing operation, protruded spikes were formed which were then press joined against the plywood surface. The spikes pierce the plywood surface and hold the tongue tightly in position. When assembling the box, the tongues were inserted into tongue slots which were produced in profile/post and then the tongue was bent backwards to 180o using tongue tool making a joint between two plywoods. Tongue locking mechanism was made for easy assembling and disassembling of the box. Also tongue joint was mainly incorporated in the box as a solution to reuse the crate for multiple shipping cycles.

**Profile making operation**

Galvanized steel of 0.8 mm thickness was used to make the profile. Profile was used only for the lid and bottom. The galvanized steel was procured in coiled sheet-form in which lancing, punching, notching, cutting, shearing and forming operations were performed to obtain spikes, tongue slots,
v-notch, cut, slit and bend on the sheet metal respectively. Figure 6 illustrates the sequential operations performed on the work-piece. Two dies performing same operations were placed on either side on the work-piece pathway. While making the profile, spikes were formed by lancing operation.

During the process of lid/bottom making, spikes were pierced into the plywood sheets using profile pressing operation. Tongue slots were punched on the work-piece at a distance depending on length and width of the box. Two v-notches produced by notching operation allow the profile to bend over the two corners of the plywood sheet. Cutting operation was performed to cut the sheet metal to the desired length and slitting operation bisects the sheet at the width-centre after cutting. Thus work piece got separated after slitting and forming operation assist the sheet to bend at 90°. Thus two profiles were produced simultaneously at the same time. Two profiles obtained with same length were press joined using profile pressing operation onto the lid/bottom covering the four corners of the sheet helps enclosing the box walls on closing.

**Post making operation**

Post was also made of galvanized steel with a thickness of 0.8 mm. The manufacturing process of making post was similar to that of profile making process. Except the notching operation in the profile process flow diagram, every other operation was unchanged for making a post. Posts were press joined using post pressing operation at the length sides and tongues were pressed to the width-sides of the box. Tongues were inserted into the tongue slots on the post and bent using tongue tool making a joint. By this way the walls of the box were joined on assembling. Since post-tongue joints were made at the corners of the box, it takes the major load on compression and stacking force.

**Klammer Joint**

Klammer was a multi-functional joint and was made using 0.8mm thickness galvanized steel. Klammer as a joint which could be used to attach two plywoods permanently or with a crease line in the centre of the Klammer allow movement between two ply-woods. Instead of using post for attaching the box length and width sides, Klammer could also be used. Klammer joint between two plywoods with outward chamfering allow the plywood to move in 180°, whereas inward chamfer allow 90°. Thus it helps in saving time during assembling and disassembling by eliminating the tongue locking operation. The strength of the Klammer was comparatively lesser than post on compression and stacking force.

Engineered plywood boxes produced with the above discussed production techniques had limitation to fulfill various real time problems. Some of the issues faced by the packaging industry have been focused in this research paper are as follows,

- Under or Over designing the package for a product
- Crate sizing problems which leads to space wastage during storage and shipment of the packaged industrial products
- Production lead-time during demand uncertainty which in turn affect the company’s overall performance rate.
In this research work, new production techniques were explored and introduced a plywood joining method which made the modularity possible with the plywood crate. Satisfying the production feasibility, new innovative conceptual modular plywood crate designs were developed.

Conceptual design-I: Expandable plywood crate

In this conceptual design, two wooden planks of identical thickness were joined using Klammer, in which one plank was nailed on to the edges of the parent box wall and the other nailed to the extendable plywood sheet (subassembly) as shown in Figure 7(a). Now, the Klammer acts as a pivot and allows the subassembly to move back and forth in 90° axis as shown in the Figure 7(b). Incorporating the same technique in all the four sides enabled the possibility of size modularization. Since the subassembly was attached permanently to the parent body, the box could be expanded to the fixed subassembly dimensions. But the expansion was possible in all the directions. Tongue-post joints were used on all the sides and the tongues were press joined onto both the edges of the walls on subassembly plywood sheet and parent body. On assembling the box to lower dimension, the parent body tongue locks into the post, whereas on the expanded size the tongue on the subassembly plywood locked into the post as shown in Figure 8. This way of extension was possible since the tongue was fixed on the outer surface of the parent body which makes no obstacle when the box was expanded.

Figure 7: Klammer Joint on box wall (a) before extension and (b) after extension

Figure 8: Expandable Plywood Crate sleeve customization (a) Sleeve with no dimensional change, (b) Dimensional change on long-side, (c) Dimensional change on short-side and (d) Dimensional change on both sides

Figure 9(a) & (b) shows the appearance of the box when no dimensional change and at maximum dimension customized respectively. The folded plywood extensions at times of no customization inside the box could take up more compression strength on stacking. This design was suitable only when the variable product sizes in a product family limited to four dimensions.

Figure 9: Complete box design-Expandable Plywood Crate (a) appearance of the box when no dimensional change and (b) at maximum dimension customized
Figure 10 shows the production workflow for producing the Expandable Plywood Crate and in which the parent box long-side and short-side production involved plywood cutting, chamfering, post making, post pressing and tongue punching operation. Klammer operation was performed only for extendable part of long-side and short-side and the extendable parts were attached to the long-side and short-side parent box through nailing operation.

Introducing this expandable design concept, prior to the customer’s requirement, the sleeves/sides of the boxes could be produced beforehand. With respect to the customer order, only lid and bottom were to be manufactured, thus every boxes need not to be produced from scratch. Since lid and bottom were to be produced to the customer order, the production workflow for manufacturing it followed the same as the conventional production flow.

Conceptual design-II: Modifiable reinforced plywood crate

For conceptual design II and III, a new production technique for joining plywood at 180° was introduced, which was termed as ‘flat post’. This flat post could be manufactured in the post/profile making machine. Eliminating the forming and notching operations in the production process of post, the obtained post was flat without the L-angle bend at the centre. Thus production of flat post with spikes and tongue slots was achievable with the reduction of cost from the current production technique. The following Figure 11 shows press joined flat post onto the plywood sheet.

Reinforcement helps improvement in box sturdiness, which ultimately improves the compression and stacking strength of the box. Here, wooden plank serves as a reinforcing material which was provided on the edges of the lid, bottom, long-side and short-side as shown in Figure 12.

In this design, the flat post was press joined to the plywood subassembly and the tongues were press joined to the lid/bottom of the parent box. The inside view of the disassembled parent lid from the subassembly part is shown in Figure 13. The tongues and flat post were press joined to the inside surface of the lid/bottom. When lower dimension was required, the protrusion of the tongue in the parent box might increase the risk of handling the box, so it was covered by the plank on top, which leaves no sharp edges.
The above flat post tongue joining technique was also used on the long-side and short-side of the box. In which the flat post was press joined onto the subassembly plywood part as shown in Figure 14. The only difference compared to the lid/bottom was that the flat post and tongue are press joined on the outside surface of the plywood sheet. Thus this design allows the box modification possible either in long-side or short-side. But dimensional change with both the sides at the same time was not possible. Since reinforcement was given, this design could be suitable for accommodating heavy-weighing products with variable sizes.

The design was modeled in such a way that the reinforcement plank size was designed to use klimp locking method. Klimp acts as clips for securing lid and bottom to the sleeve, which could be easy to put-on and put-off. Thus it would solve the problem of box assembly/disassembly for returnable and knock-down crate boxes. Instead of using Klimp, L-clamp also could serve the same purpose, but screwing and unscrewing would increase the assembling time.

The production workflow for the conceptual design-II is shown in Figure 15, the production process was same for making the parent box and sub-assemblies. The conventional post and flat post were produced and joined using the same machine. The reinforcing planks were fixed onto the plywood by nailing operation. Producing the parent box and stocking up in inventory prior to the demand would
reduce the lead time and the sub-assemblies could be produced and assembled with the parent box with respect to the customer requirement.

**Conceptual design-III: Modifiable plywood crate**

Flat post tongue joint was introduced in this design. This design does not involve any reinforcement and the entire box was designed using 7.5 mm plywood thickness and the attachment of sub-assemblies was done by flat post tongue joint. In this design, all the flat post and tongues were press joined to the outer surface of the plywood sheet. This design could be best suitable for accommodating products of medium weight.

As the Figure 16(a) illustrates the flat post tongue joint was made at the centre of the lid/bottom in the parent box which enabled the provision for customizability function but the customization was possible in only one direction. The subassemblies were attached to the lid/bottom and to the sides of the box with respect to the customer demand. Similar to the conceptual design-II, the flat post was press joined to the subassembly plywood sheets and tongues were press joined to the parent box. As shown in Figure 16(b), the lid/bottom subassemblies were attached to the centre of the parent lid/bottom and long-side or short-side subassembly was attached to the corners of the parent long-side or short-side at the time of customization.

![Fig. 15: Production workflow - Modifiable Reinforced Plywood Crate](image)

![Fig. 16: Modifiable Plywood Crate (a) parent box and (b) customized box](image)

![Fig. 17: Box long-side facilitating flat post tongue joint](image)

While joining the subassembly to the parent body, the tongue got inserted into the tongue slots only at an angle of 120° and then on bending the tongue backward using tongue tool make the joint straight to 180° as shown in Figure 17. Although the variation in dimension was possible in one way, looking at the simplicity of the design, the production seemed to be trouble-free and effortless.
As like the conceptual design-II, the parent box dimension could be manufactured beforehand and on customer requirement, only the sub-assemblies need to be produced. As far as this conceptual design was concerned, multiple sizes of attachable plywood subassemblies could be produced in order to modify the box to different dimension in one direction. The production workflow is shown in Figure 18, parent box and the sub-assemblies can be manufactured using fewer operations compared to other conceptual designs with the inclusion of flat post tongue joint and the production eliminated the nailing operation completely.

**Analysis and Discussion**

Each conceptual design box dimension for adapting modularization technique could be done by knowing the product size varieties from the customer (collaborative customization). Every conceptual design was modeled to satisfy the function of collapsibility, thus permitting disassembling and stacking of the box in a collapsible form which could eliminate the space of stacking as a whole cube pack in the warehouse and transport. The proposed conceptual designs were modeled to adopt design and product adaptability. As the conceptual designs could be modified to the product size variation at the design phase, design adaptability was evident and also the customization after the design production would allow the customer to resize the crate for the desired dimension which clearly shows that the adaptability could be achievable at the production phase too. Also every design uses only tongue-joint locking method for assembling and disassembling, the locking/unlocking can be done using a tongue tool, which were already in use for the current plywood box and required no special tools for achieving customization.

**Collaborative Design Performance (CDP) Matrix**

Based on the performance of each conceptual design, a matrix called Collaborative Design Performance (CDP) Matrix was constructed and is shown in Table 2, with respect the design performance measurement [15]. It served as an effective tool for analyzing the design Parameters of each conceptual design to its Performance. Choosing the design performance parameters as customizability, sustainability, ease of production, lead time reduction, cost effectiveness, ease of assembly and disassembly, the justification for each conceptual design from the projected analysis is given below.

![Fig. 18: Production workflow - Modifiable Plywood Crate](image-url)
Conceptual design-I

As inferred from the design, once an Expandable Plywood Crate was manufactured, the dimensions could be modified in all four fixed dimensions. Within the four fixed dimensions, the box could be modified in length-wise, width-wise and both sides simultaneously. Customization could be done in a short time satisfying the ease of assembly and disassembly to the fullest due to the provision of Klammer, which would act as a joint for joining the extendable plywood part and also as a built-in customizability function. Although cube optimization satisfied fixed customization to the fullest, in the case where no customization was needed, then the folded plywood sleeve inside the box becomes redundant and would add up weight during freight/shipment increasing the shipment cost, which becomes the reason for mapping the cost effective
and sustainability with partial fulfillment. During uncertain demand, only lid and bottom need to be manufactured reduce the lead time but it was mapped with half-fulfilled because postponing the complete production of lid and bottom increased the lead time in comparison with other conceptual designs. The mapping between process commonality and ease of production was partially fulfilled because klammer joint and nailing operation increased the production time and requires more workmanship. The sleeves were no separate sub-assemblies, so sorting and stacking in warehouse and transport required less floor space compared to other conceptual designs.

Conceptual design-II

Modifiable Reinforced Plywood Crate facilitates variable customization in length-wise and width-wise direction. Prior to the customer requirement, the parent box of lower dimension could be manufactured and on demand, only the sub-assemblies need to be produced reducing the lead time. Thus it satisfied the postponement and lead time reduction completely. But production of sub-assemblies along with the plank reinforcement required nailing operation, which is why the ease of production and lead time reduction with uncertain demand was mapped as half fulfilled. Compared to the conceptual design-III, this design required more material for achieving customization, which was the reason for mapping sustainability as half fulfilled with cube optimization and raw material consumption. Common production process for making parent box involved wooden plank trimming operation and nailing operation, for which manual intervention was needed eventually increased the production time, thus the process commonality was mapped as half fulfilled with ease of production. A major advantage of this design was that the sub-assemblies could be attached to the parent box when needed, thus it would eliminate the shipping cost for carrying the customizability modules along with the box when lower dimension preferred, which became the reason for mapping cube optimization with cost-effective and variable customization as completely fulfilled. Also this design does not included tongue joining method for enclosing lid and bottom, thus assembly and disassembly became easy.

Conceptual design-III

Modifiable Plywood Crate could ensure customizability in one direction either in length-wise or width-wise. But unlike the conceptual design-I, various dimensional subassemblies could be produced and attached to the parent body depends on the customer requirement, thus increasing the customizability function in that direction. Compared to other two conceptual designs, this design completely modeled using tongue-post and tongue-flat post joint, thus assembly and disassembly required some time for customization. Knowing beforehand the variable product sizes, the standard lower dimension parent box could be manufactured individually with the provision of customization either in length-wise or width-wise direction. Thus on customer demand, the subassemblies need to be manufactured. Since the production of parent box and sub-assemblies could be done using plywood material alone, the process commonality completely fulfilled the ease of production. Also, the customization became possible with the flat post tongue joint and required no plank or klammer joint, the raw material consumption was less compared to other conceptual designs, which also became a strong reason for mapping cube optimization and raw material consumption with cost effective as completely fulfilled. Mapping uncertain demand and postponement with lead time reduction as completely fulfilled was because this design required no extra features or operation for production compared to other conceptual designs reducing the production time completely.
Order Penetration Point (OPP)

Order Penetration Point (OPP) is the point where the customer order is placed in the manufacturing value chain. Before that point, the flow of chain is controlled by the demand forecasted and after that point the delivery was made to the customer order. For producing variable product sizes for a product family, conventional manufacturing strategy was non-linear in its production flow. Once the order was placed by the customer, the order was processed from the design stage and so conventionally, the strategy was Engineer to Order (ETO). Whereas, adapting design modularity and collaborative customization, the developed innovative conceptual designs could adopt Configure to Order (CTO) manufacturing strategy. Figure 19, shows the production flow and the order penetration point of conventional manufacturing strategy, where in this case the customer placed an order with three product varieties to the packaging industry. The orders were engineered and designed at the design phase for three product sizes and each product size need to be manufactured separately and simultaneously in the production flow, which was the reason for providing three arrows linking every stage in the flow. Every box was distributed in collapsed form from packaging industry to customer place, thus separate floor space was needed for each box size in truck and warehouse.

Figure 20, shows the production flow and the order penetration point of the proposed conceptual designs manufacturing strategy, where in this case forecasting the demand, the parent box (lower dimensional boxes) with customizability function to attach variable size dimension sub-assemblies were to be produced and stocked in the inventory. As all the parent boxes produced would be of same dimension, very low inventory maintenance would be needed. On the placement of order by the customer, only the sub-assemblies need to be made and assembled with the parent box and delivered to customer. The process postponement on customer demand was achieved through design modularity and it would serve as a proactive approach at uncertain situations.
CONCLUSION

From the Collaborative Design Performance (CDP) Matrix and order penetration point (OPP) analysis, it is evident that the reengineered designs adopt product commonality and postponement in an effective way. The results indicate that every conceptual design has its own limitations and advantages over other. But every conceptual design fulfills the functions of a distribution package. As a modular design, each conceptual design is best suitable for different product family with product variability.

- **Expandable Plywood Crate** - This design is best suitable when the product variety is small (<5 no’s) and confined to fixed dimensions. This design is also fit-in where rapid customization is required, as the customization is easy, simple and not time consuming.

- **Modifiable Reinforced Plywood Crate** – Since reinforcement is provide, this design satisfies where modularization and high box compression/stack strength is demanded by the customer. Also this design satisfies its purpose completely where product variety is high. Since reinforcement is provided and easy assembling/disassembling technique is incorporated, this design is appropriate where returnable modular packaging is required.

- **Modifiable Plywood Crate** – This design is best suitable where the product size variation is high in any one axis. Also, this design serves as a sustainable packaging solution with modularity function. Since the production is hassle-free and lead time for sub-assembly production is minimal, this design is appropriate where uncertainty is high.

Future research work can be done in the facet of various packaging materials like steel crates, metal drums and reinforced plastics. The modular pack designs which are developed can be used to various engineering applications like electronic goods, food and perishable products which save production time and improvise the efficiency of the company from an early bird view. The joints which have been incorporated into the design are the key factor which withstands the stresses in the package during transportation and warehousing. The efficiency of the transport packages can be achieved by varying and analyzing the material, design and position of the joint in the package. Since industrial packaging is an evergreen field, developments from every dimension for package source reduction will serve as an economic and sustainable solution for the future.
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Modular Crates – A Holistic Design Approach 54