Gearbox Development for the Food and Beverage Processing Industry

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Introduction

The importance of Food and Beverage (F&B)-related businesses to the gear industry cannot be emphasized enough. The F&B industry has generated 11% ($1.2 billion) of total geared product revenue in 2016 (Ref. 1). The machinery demand driven by the general population will continue to grow so as to serve the increased consumption of processed and packaged food.

Food safety is the paramount concern for F&B industry; about one in six Americans are affected by food-borne diseases (Ref. 2). A study attributed by USDA's Food Safety and Inspection Services (FSIS) shows that *Salmonella, Listeria monocytogenes (Lm),* and *E.Coli O157:H7* are the most common bacterial pathogens to cause foodborne illness in ready-to-eat products that are mainly categorized under meat, poultry and dairy (Ref. 3). Food processing- and packaging-related practices are regulated by federal and state bodies; among them are the FDA (Food and Drug Administration), USDA (United States Department of Agriculture), NSF (National Sanitation Foundation), and 3A sanitary standards. The recently implemented FDA Food Safety Modernization Act (FSMA) dictates aggressive steps to curb such diseases in early stages. NSF standards establish minimum food safety and sanitation requirements for design, construction, materials and cleanability of food handling and processing equipment (Refs. 4–5). All these regulations uphold the best food safety industry practices and protocols, the compliance of which protects the manufacturers from penalties and product recalls.

Leaders in the F&B industry prefer equipment built with stainless steel material because of its versatility, including its corrosion resistance properties. Stainless steel withstands the chemicals utilized in cleaning and sanitizing procedures adopted by the industry.

The motivation of this paper is to understand and discuss the gearing system feature requirements for F&B equipment, and efficiently adopt those features in an existing gearbox currently offered by the company (Ref. 6). This paper describes a redesign approach to develop a new gearbox product that meets requirements laid down by food safety regulations. The existing gearbox design is analyzed against the needs and innovation using QFD, FMEA, FEA and 3-D printing tools. The selection and redesign of components shown in Figure 1 is the objective of this paper. The next section briefly describes the background of the product development method utilized to accomplish the mentioned objective.

Literature Survey

In the late 1960s, Japanese administration invested in finding a system to ensure that the final product would be linked to satisfying customer requirement. The outcome of it, called Quality Function Deployment (QFD), was implemented in building supertankers (Ref. 7). This method was perfected in later years, and adopted by Japanese as well as American industries. QFD is used to determine and focus on the essential functionality features of the product. It is usually implemented in the early stages of product development. It is a well-known communication and brainstorming tool (Ref. 8).

Failure Mode and Effect Analysis (FMEA) is a quality tool utilized for analyzing failure modes against the functionalities of the product. It was developed in the 1950s by reliability engineers to solve issues in military systems (Ref. 9). This

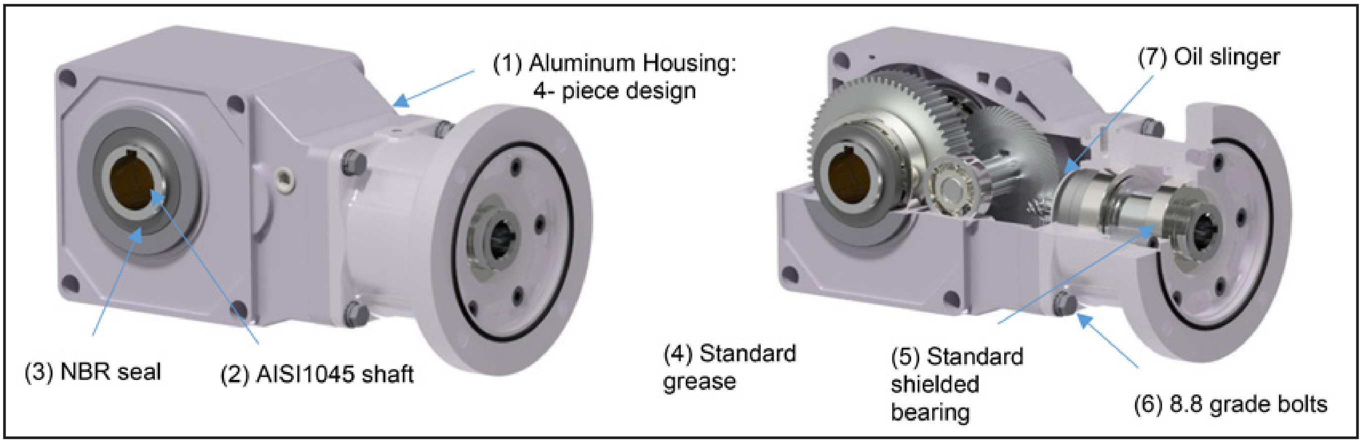


Figure 1 Existing gearbox to be redesigned for F&B applications.

tool is known for achieving high reliability in both, products and processes (Ref. 10). The main procedural steps of FMEA are defined as follows:

1. Clarify function of each system, component, or process elements.
2. Investigate root cause, failure modes and failure probability based on the function, interaction with other components, and environment.
3. Study the effects of problems, and prioritize casual factors.
4. Recommend actions.

Regarding QFD and FMEA, both tools require a systematic process to define 'what' and 'how' (cause and effect) relationship, and prioritize them. They tend to shift the cost, efforts and discovered problems away from the product launch timing (Fig. 2).They both assess technical details to identify further actions and recommend testing. Both demand cross-functional teamwork and contributions for successful implementation. The distinct difference in these two techniques is at what product development stage they are implemented. The FMEA approach is more production-oriented, and QFD is generally used in early stage (planning) of the product development cycle.

Ginn, D.M. et.al. discusses a methodology of integrating QFD and FMEA tools at conceptual, planning, design and processing stages of the product development (Ref. 11). The paper adopts this methodology and elaborates the simultaneous use of both tools at each stage.

As shown (Fig. 3), FMEA and QFD are interlinked at each

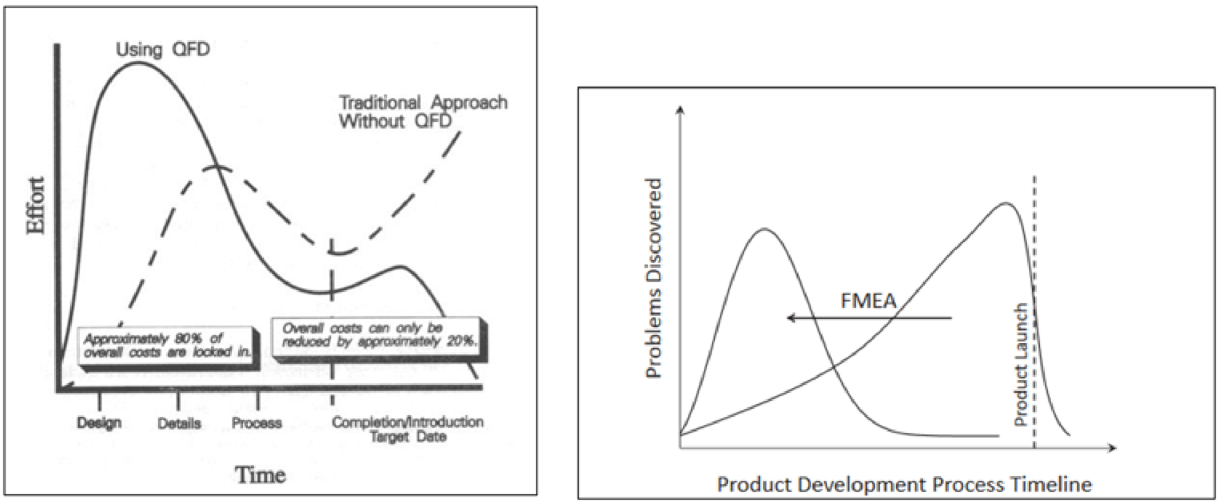


Figure 2 QFD & FMEA tend to shift development efforts and discovered problems towards earlier stages (away from product launch) (Refs. 7, 10).

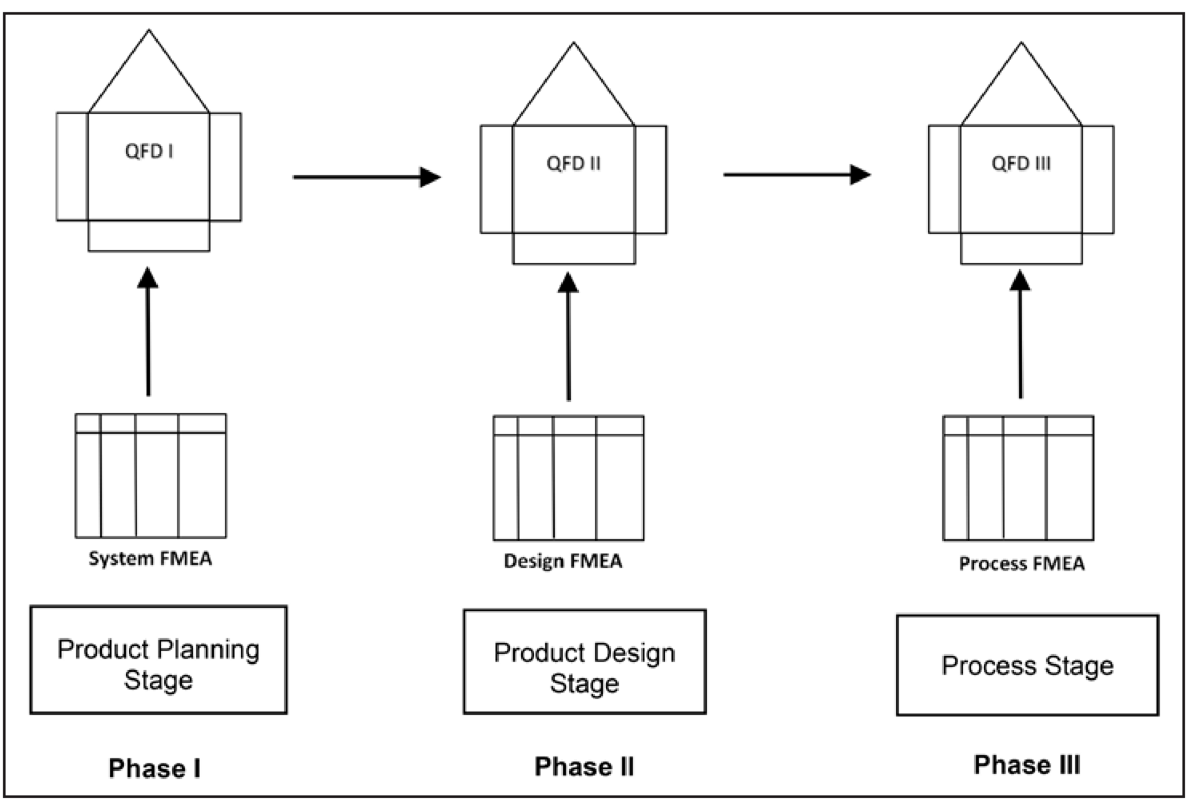


Figure 3 Integration of FMEA and QFD at each product development phase.

Table 1 QFD I - Product Planning

	Column #	1	2	3	4	5	6	7	9
	Direction of improvement Minimize (▼), Maximize (▲) or Target (x)	x	▼	▼	▲	▲	x	x	x
Weight/ Importance	Technical requirement ("Hows") / Application requirement ("Whats")	Housing material: Stainless steel OR Composite	Optimized lubricant (Grease) quantity	Thermal rating greater than Mechanical rating	Torque/ Weight ratio	No outer cavities on housing	Bolt holes at Bottom	Bolt holes at casing Face	Externally visible components - NSF complied
10	Corrosion Resistance/ NSF Compliance	9	3			9			9
9	Light Weight (for shaft mount)	9	1		9				
7	Multiple mounting options					3	9	9	
7	Cleaning friendly housing contour	1				9	1	1	
9	Acceptable housing surface temperature	9	9	9		1			
8	Adequate surface roughness for cleaning	3				1			
5	Torque capacity up to 2000 in-lbs	3		3	9				
9	Market level cost	9							
9	IP69K standard Certified	3				3			

stage of the product development cycle. QFD evaluates and determines the options and features to be incorporated into the product, and FMEA checks for the failure modes. Accepted features from FMEA process are considered for the next stage.

Table 2 Physical property difference between existing and new casing material

Property	Unit	Existing casing material: Die Cast Aluminum (ADC12)	Proposed Casing Material	
			Cast stainless steel (CF8)	Composite (Custom made)
Density	Kg/m^3	2760	7750	~1600
Mod. of Elasticity	MPa × 10^3	71	193	11
Yield strength		165	205	-
Ultimate strength		331	485	~200
Thermal conductivity	W/m-°K	92	20.94	~4

Product Development — Phase I

The important 'requirement' related to food safety regulations is food contact materials, i.e. — the surfaces which directly or incidentally come in contact with the food. These surfaces should be smooth, non-porous, durable, and free from corrosion, pits or food particle accumulation. Food contact materials classification basically applies to the external surface(s) of the gearbox. External surface area exposed to the outer environment comprises of casing, shaft, hardware and seals. Washdown requirements defined with IP69K (Ingress Protection standard to rate the resistance to dust and high-pressure wash) are derived from industry practices. Torque range and mounting options (foot and shaft mount) are finalized from market research and competition offerings.

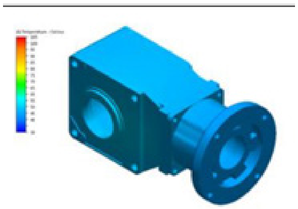
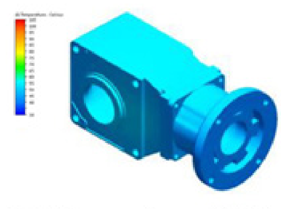
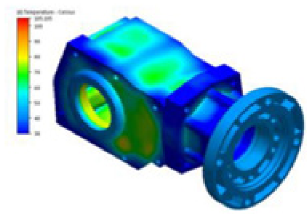
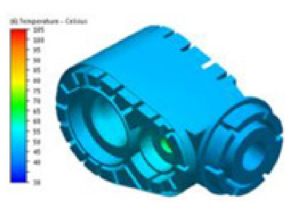
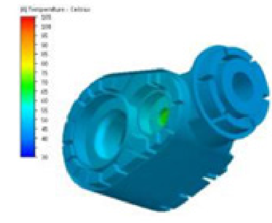
The existing gearbox meets the torque range requirement, but shows deficiencies in offering mounting options, and aforementioned properties required for food contact materials.

In product planning QFD (Table 1), different ideas and

Table 4 System FMEA

ITEM	Function	Potential Failure Mode	Effect of Failure	Severity	Potential Cause(s) of Failure
Gearbox must provide features required for food equipment, in compliance with food safety regulations	Provide corrosion resistance	Corrosion Crevice corrosion	Fatigue; Health hazard	9	Casing surface corrosion due to chemical washdown
	Sanitary equipment design (Ease of cleaning)	Accumulation of food particles	bacteria growth in cavities; Health hazard	10	Existence of surface cavities
	Keep gear lubricant contained from food	Lubricant leakage	Food contamination	10	Seal leakage
	Provide appropriate speed and torque	Cannot operate the application	Economical loss	10	Internal component (viz. gear, bearing, shaft) seized or failed
	Mounting options	Does not meet F&B application requirements for mounting	Not appropriate for installation	7	Mounting versatility not available
	Connect to equipment shaft	Does not meet F&B application requirements for mounting	Not appropriate for installation	5	Shaft connection options not available

Table 3 Comparison of CFD analyses for casing surface and lubricant temperatures

Thermal analysis (at ambient 20°C)	**Existing AL material**	**CF8 Stainless steel** (Analysis performed on existing design)	**Composite** (Analysis performed on preliminary design)
Casing surface temperature	 Wall Temperature: 48°C	 Wall Temperature: 56°C	 Wall Temperature: 64°C
Lubricant temperature	 Wall Temperature: 50°C	 Wall Temperature: 62°C	 Wall Temperature: 94°C

suggestions, influencing directly or indirectly the defined requirements, are brainstormed. They are weighed based on their influence, either 9 (strong relation), or 3 (moderate relation), or 1 (weak relation). These relations are decided by a cross-functional team, which is formed by the members of multiple departments. Stainless steel and composite are two casing material options shortlisted and proposed to replace existing aluminum alloy ADC12 (die cast aluminum). In comparison with ADC12, the proposed materials may offer better corrosion resistance, but they lag in providing equivalent thermal conductivity (Ref. 12). In the composite material option, both thermal conductivity and material strength are in question. Material strength cannot be easily analyzed (analytically or numerically) because of an anisotropic nature of the composite material.

At this early stage of the development, predicting behaviors of both materials under functional conditions, and picking the best suitable material for the next development phases would significantly impact valuable resources: development time and cost. Changing the material in later stages would reset the entire development cycle. Physical properties of the proposed materials and the existing casing are compared in Table 2.

Both material options are evaluated based on System FMEA recommendations and compared (Table 4). Though the composite material would provide better chemical resistance, it has scored less on providing appropriate structural strength and thermal conductivity, when checked with Finite Element Analysis (FEA). Table 3 shows the results of numerical analyses of thermal characteristics for different casing materials, using computational fluid dynamics (CFD).

Stainless steel is found more suitable to be utilized as a 'food contact material' in the gearbox system. For casting parts, such as housing, CF8 cast steel grade is selected. For

Occurrence	Current design control (Prevention)	Current design control (Detection)	Detection	RPN	Recommended Actions
9	Aluminum casing (ADC12) with antimicrobial coating	Discoloration, Paint peeling, Cracking	4	324	Evaluate stainless steel and composite materials for corrosion resistance, as well as to substitute existing Aluminum (compare strength, temperature).
8	None	Any outer cavity susceptible to bacterial growth	10	800	A. Redesign casing with 1. surface roughness of 125 micron 2. Consistent outer surface, absence of gaps B. Design mounting accessories without cavities. C. Hardware selection with no cavities.
6	Appropriate seal installation	Visual inspection	8	480	1. Select Food grade lubricant with NSF H1 rating 2. Select more robust seal for washdown application 3. Food grade gasket
2	Gearbox selection based on application (demand) torque and speed	Application stops running	2	40	No issues found with existing design. No action required.
5	Only shaft mount arrangement available	Customer survey	2	70	Develop flange and torque arm mounting options
5	Keyed hollow bore, Shrink disc connections available	Customer survey	2	50	Develop solid output shaft option

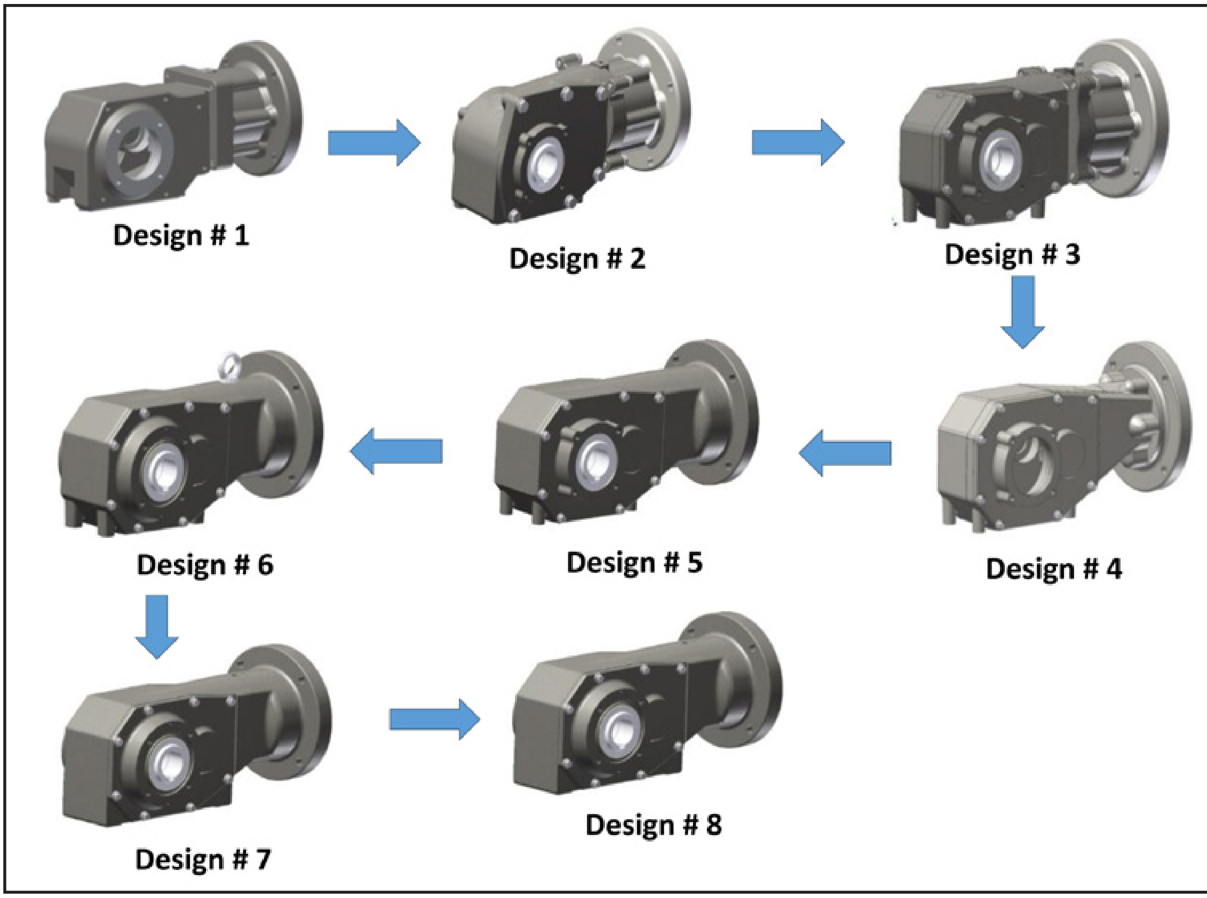


Figure 4 CAD models- From # 1, which is similar to the existing four-piece design, the casing evolved into a three-piece design on the 8th iteration.

Table 5 QFD II – Design

Weight/ Importance	Column #	1	2	3	4	5	6	7	8	9	10
	Direction of improvement Minimize (▼), Maximize (▲) or Target (x)	x	x	▲	x	x	x	x	x	x	▲
	Technical requirement ("Hows") / Application requirement ("Whats")	Investment Casting Process	Structure strengthening with ribs	Round-like shape/ contour	Corrosion resistant output shaft	Washdown resistant output Seal	Accessory- Floating Torque arm	Accessory- Flange	3- Part casing design	Food Grade Grease ZZ bearing	Additional SS parts
10	Housing material: Stainless steel	9	9	3		1	1	1	9		
8	Optimized lubricant (Grease) quantity		3	3		1			3	1	
7	Thermal rating greater than Mechanical rating										
7	Torque/ Weight ratio		9				1				
9	No outer cavities on housing	1		9					9		
6	Bolt holes at Bottom						9				
7	Bolt holes at casing Face							9			
9	Externally visible components - NSF complied				9					9	9
	Target or Limit Value	5 to 12 mm thk, 100 - 125 RMS roughness	2.5 SF over gear torque + dead weight	0.56 Kg	AISI 304	Cassette seal					

Table 6 Result of Design QFD

#	Part	Changes to existing gearbox assembly: New features/ parts	Changes to existing gearbox assembly: Existing features/ parts
1	Housing	Cast steel (CF8) housing parts (four piece)	Aluminum (ADC 12) housing parts (three piece)
2	Output connection	AISI 304 manufactured output shaft	AISI 1045 manufactured output shaft
3		Nickel plated shrink disc offering as an option	Standard shrink disc
4	Output seal	Cassette Seals: Food grade and washdown compatible	Standard double lip NBR seals
5	Lubricant	Food grade grease	Standard grease
6	Bearing	Food grade shielded bearings	Standard shielded bearings
7	Nameplate	Laser etched nameplate	Steel nameplate riveted on Housing
8	Plugs	Nylon (plastic) plugs: to plug unused housing holes	n/a
9	Hardware	Stainless steel bolts (hardware)	8.8 grade steel bolts
*	Accessory parts	Stainless steel floating torque arm	Do not exist
		Stainless steel output flange	

output shaft and hardware, wrought steel AISI 304 is chosen.

CF8-grade cast steel is selected because of its corrosion resistance property, availability and customers' acceptance. Stainless steel casting is considered 'corrosion resistant' when used in aqueous environments below 1,200°F. Low carbon content (below 0.2%) and higher chromium content (above 16%) used in chemical composition enhances corrosion resistance. The austenitic (CF) grade of this casting family is generally preferred for chemical, pharmaceutical, and food industries. CF grade is resistant to most of organic acids, compounds used in aforementioned industries. Corrosion resistance properties mainly come from a passive surface film that protects from the surrounding environment. This film is formulated and stabilized by maintaining the minimum amount of chromium content in the casting's chemical composition.

Stainless steel does not alter the taste, color or odor of the food when in contact with it for a prolonged period of time. This includes the use of stainless steel for food preparation, processing, transportation and storage. Stainless steel's resistance to several alkaline cleaning agents is proven. Several experiments show that the release of chromium and nickel under the influence of acids is very low or negligible (Ref. 13).

Other components exposed to the outer environment are also listed to be replaced. For instance, the seal can have better water and chemical resistance. The output shaft and mounting accessories could be modified to meet the same purpose.

With the existing design as a reference, different patterns, shapes and variations are created and reviewed. The most apt design for F&B application is chosen based on its emphasis on smooth contours, no external cavities or pockets, optimized weight, optimized internal volume, optimized machining area, and mounting arrangement considerations (Fig. 4).

Product Development Phase II

Part level QFD is performed after finalizing system level options with Product Planning QFD and System FMEA. 'Hows' from QFD I become 'whats' in QFD II to determine part characteristics (Table 5). In the redesign process, the list of items shown in Table 6 would be incorporated in the gearbox assembly.

Housing parts are developed such that the heat dissipation

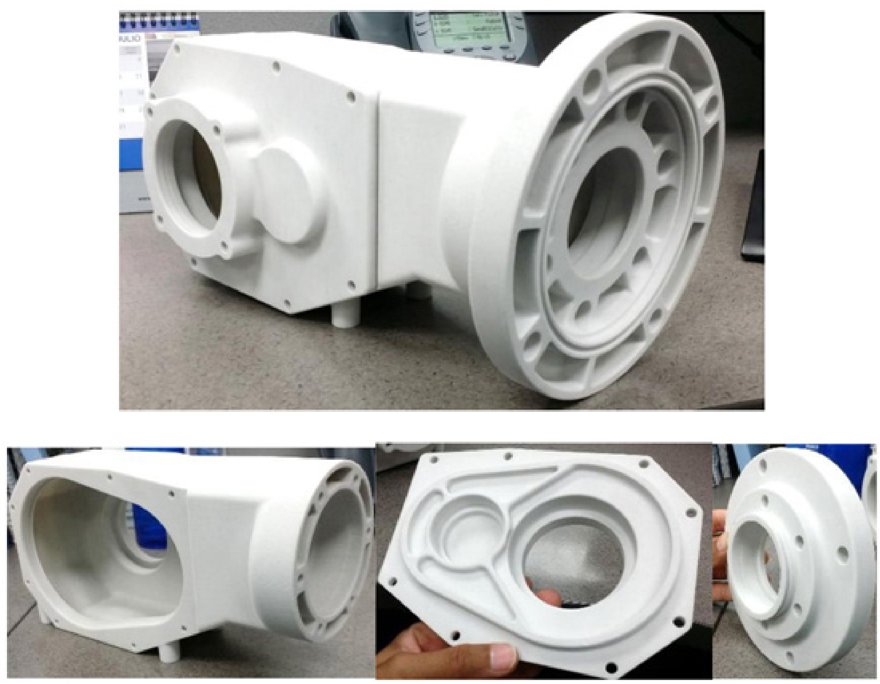


Figure 5A 3-D printed parts' assembly at design iteration #5.

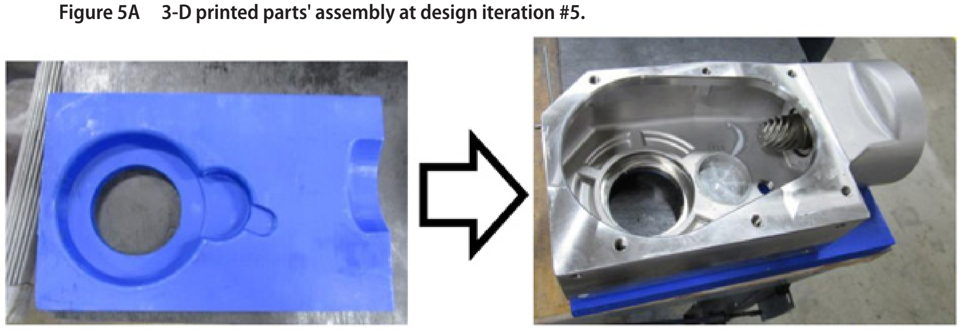


Figure 5B 3-D printed fixture testing.

Figure 5 Examples of the utilization of 3-D printed parts.

and weight increase issues would be addressed. Design FMEA is used to identify part level failure modes (Table 7). Effective system output produced by System FMEA will be used as an input for the design FMEA, which in turn becomes input for the process/assembly FMEA (Ref. 14). Before developing actual housing prototype parts for testing purposes, a digital prototype (Computer Aided Design, or CAD model) is iterated and refined with the help of 3-D printing tools and FEA.

3-D Printing

The 3-D printer processes STL format files of the components created using CAD software. 3-D printing of the parts, after each major iteration, has made it possible to reduce errors associated with the geometry of the new parts (Fig. 5A). CAD modeling validation and component assembly areas are particularly benefited by 3-D printing technology. For instance, in case of CAD modeling, a thorough inspection of 3-D printed part has revealed an extra length of a tapped hole located on the outer surface of the housing breaking into the internal cavity.

Table 7 Design FMEA for Cast stainless steel housing

ITEM	Function	Potential Failure Mode	Effect of Failure	Severity	Potential Cause(s) of Failure	
					Primary	Secondary
Housing parts (Casing, Cover, and Adapter)	Support Gear loading	Deformation under load	Lubricant leakage, Vibration, Bolt shearing	10	Demand Overload Motor Startup load	
					Insufficient static strength	Cast steel material property is inadequate
					Casing defect	Cast porosity
	Support reaction torque (torque arm connection, Flange connection)	Deformation under load	Lubricant leakage, Vibration, Bolt shearing	10	See 'Support Gear loading'	
	Support Bearing	Bearing looseness	Vibration and noise	7	Bearing spins in the bearing housing	Improper tolerance on bearing housing
						Inadequate Surface finish
	Heat Dissipation	Higher lubricant temperature	Shorten grease life (< 2000 hours) Hypoid pinion failure	9	Inadequate heat dissipation through Casing wall	Casing surface area
						Heat conduction of SS material
					Less airflow around Unit	Lack of forced convection
					Higher Ambient temperature	Less heat dissipation due to small temperature difference (ΔT)
			Higher internal pressure build-up		See potential causes of 'Shorten grease life'.	
		Freezing of lubricant (Grease)	Gearbox 'cold start' issue	10	Low ambient temperature	Lubricant's inadequate (higher) viscosity at low temperature
	Protect internal components from Environment	Seal failure	Lubricant leakage	10	Internal pressure	High lubricant temperature
					Temperature incompatibility	Seal material cannot withstand temperature
					High pressure washdown	
		O- ring (Cover) failure	Lubricant leakage	8	Internal pressure causes lubrication leakage	Improper fit in O-ring groove
	Provide alignment to the rotating parts	Component misalignment	Premature component wear out, Noise/ Vibration Fatigue	7	Out-of-tolerance casting machining	Deviation of tolerance from print
	Anchoring	Failure of mounting holes, part deformation	Equipment damage	10	Inadequate mounting hole pattern	High stresses generated in Assembly
	Provide required properties for F&B Application	Crevice corrosion Galvanic corrosion Pitting corrosion	Unfit for application	10	Inappropriate passivation on cast steel parts	
				8	Contact with 'not-recommended' chemicals	
		Stress corrosion	Premature (fatigue) failure	10	Prolong contact with Chlorides	
		Seal failure	Lubricant leakage		Loose oil seal OD fit	Inadequate surface friction
						Oil seal shrinkage due to chemical incompatibility
					Increase in internal pressure	High lubricant temperature
						High Grease to Air ratio inside the box

For gearbox assembly, 3-D-printed housing parts are used to identify assembly interference, and components' assembly sequence. Assembly testing and subsequent changes elaborated in Figure 12 are performed using 3-D printed parts. 3-D-printed assembly jigs and fixtures are developed and modified to test the process at each major iteration (Fig. 5B).

Finite Element Analysis

Finite Element Analysis (FEA) is an efficient way of carrying out part and assembly optimization on a variety of design options, helping to narrow down to the best fitted one. Structural, modal and thermal analyses are commonly performed utilizing this tool. However, the reliability of the results depends upon the assumptions made at the time of defining and building the analysis model. This tool undoubtedly helps to expedite through QFD and FMEA processes. The FMEA generated 'recommended actions' are validated through FEA before performing actual testing (see Table 7 as an example). Conclusions on each analysis can be drawn quickly to move along.

	Occurrence	Designed Value		Detection	RPN	Recommended Action
Tertiary		Measure	Criteria			
	5	Stiffness, Stress	Support Assembly inertia, and minimum 250% motor torque.	9	450	FEA validation
	6			9	540	
	5	Number of sand holes per area	Max. 2 sand holes on a machined surface	5	250	UT sampling
Design defect	4	Bearing-housing fit	Prototype parts' tolerance study	5	140	Vibration test
	4	Surface finish	125 micron (check manufacturer's recommendation)	6	168	Surface roughness testing
-	7	Surface area	Min. 2000 hour grease life	9	567	Life test
	7	N/A				N/A
Absence of motor fan	6		Motor fan mandatory in worst case	10	540	Thermal testing
	6	Ambient temperature	Maximum ambient temperature 40 °C	9	486	Thermal testing
	3	Lubricant viscosity	Viscosity < 9000 cSt at a given min. temperature	6	180	Viscosity calculation/ Testing
	5	Internal pressure	5 - 7 PSI pressure	8	400	Testing
	5	Seal material	Compatible to temperature range 20°F to 104°F	7	350	Testing
	5	Pressure wash	IP69K ingress protection	7	350	Test to qualify IP69K
Wrong O-ring selection	2	Internal pressure	5 - 7 PSI pressure	8	128	Air Pressure test
Machining vendor cannot meet the tolerance requirement.	7	Tolerance	within 50 micron	8	392	Review of PPAP process
	4	Material stiffness	Support Assembly inertia, and minimum 250% motor torque.	5	200	FEA validation
	3		Passivation per ASTM A967	2	60	Salt Spray test per ASTM B117 standard, as defined in NSF/ANSI 51
	7		Define 'compatible' chemicals for washdown	2	112	Mention in Operation and maintenance manual.
	6			2	120	
	5		Housing bore machining roughness	6	270	
	4		Define 'compatible' chemicals	8	288	
	2		200°F maximum	5	180	
	2			4	72	

Finite Element Method solves problems numerically by discretizing or meshing the structure. In Computer Aided Design (CAD) based finite element analysis (FEA), solid model geometries are usually imported directly in FEA environment and analyzed for critical stresses and deformations under specific loading conditions.

In system FMEA, at the conceptual design stage of the product development, composite and stainless steel (cast steel) materials are investigated for F&B application. Stainless steel is chosen to develop the housing for phase II. This material brings higher structural strength compared to existing aluminum material, along with less heat conductivity. In the redesigning process, the housing wall thickness is optimized to balance the heat dissipation and the structural strength. The FEA results are considered for the housing strength; however, the heat dissipation is validated from the actual testing. It is observed that the temperature related numerical results (from the CFD tool) depend upon multiple and complex assumptions, and not precise enough to be considered in the final decision making.

FEA is performed with two models. In the first one, bearing loads are determined by running dynamic (geometrically

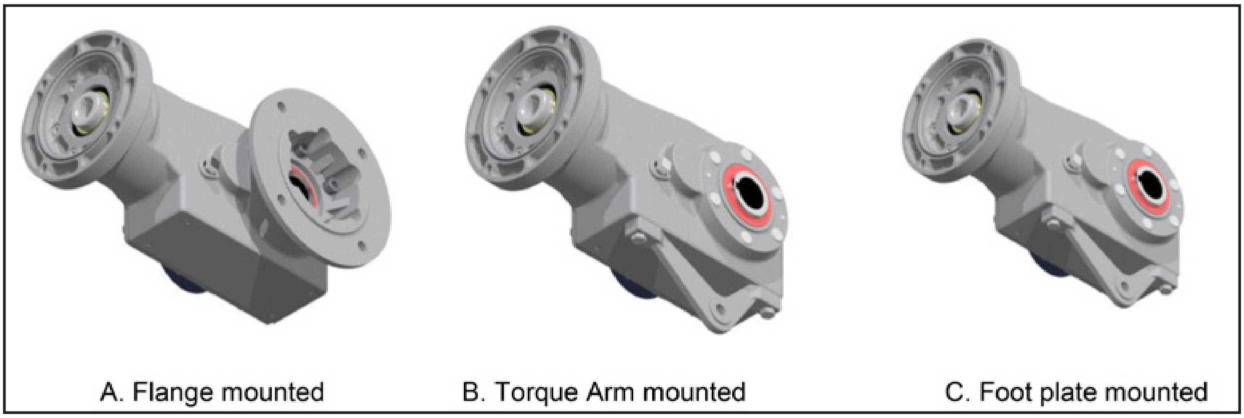


Figure 6 Development of gearbox mounting options.

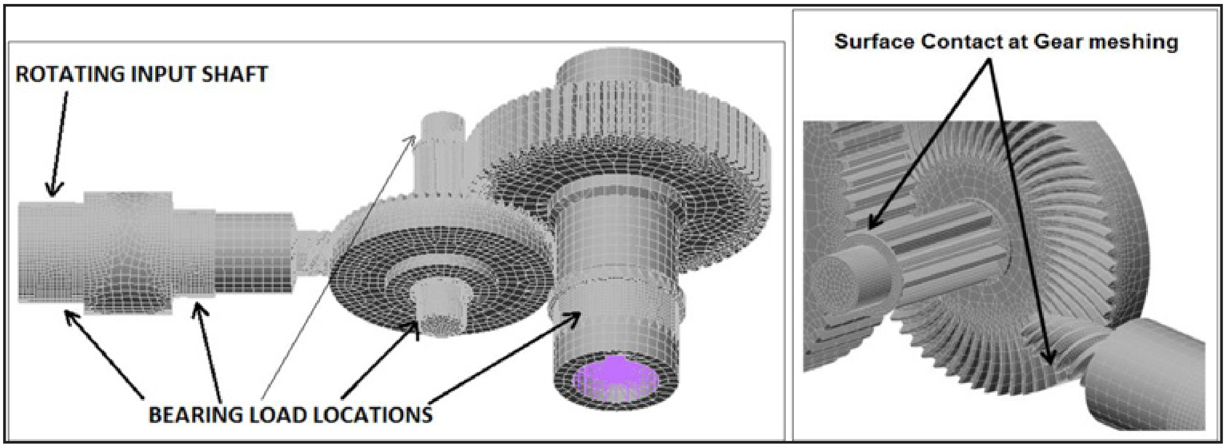


Figure 7 Meshing of internal parts' assembly, and gear meshing surface refinement.

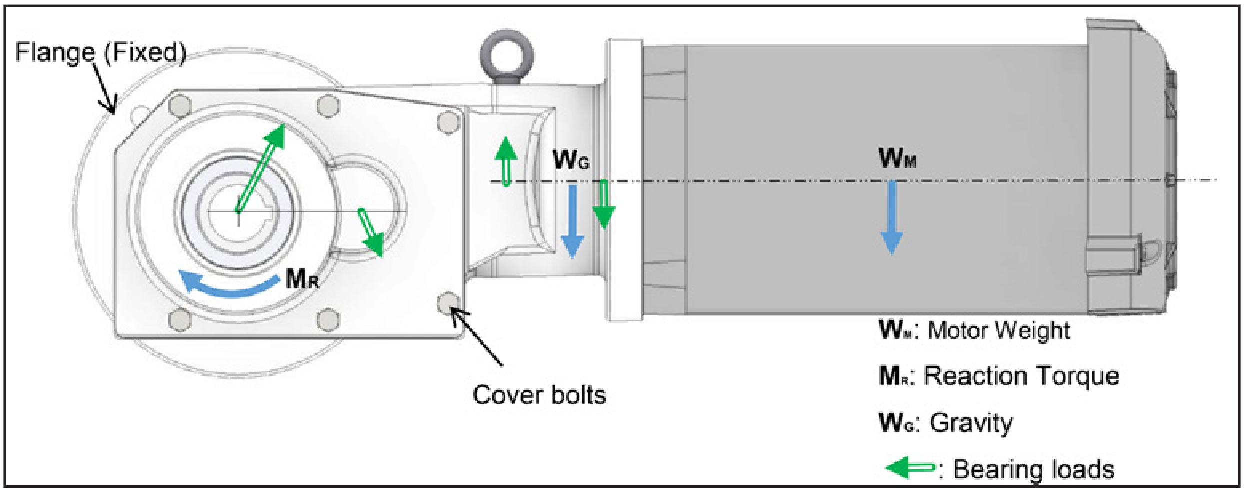


Figure 8 Loads acting on flange-mounted horizontal gearbox.

nonlinear) analysis. In the second model, the determined bearing loads are applied to stainless steel casing parts to find Von Mises stresses and deformations. The second model is simulated in a static analysis environment.

Table 8	Loads on the casing parts		
	Load	Description	Acting at
1	Motor Weight	Largest motor (145TC frame size)	C.G. of motor
2	Bearing radial loads	Imported from dynamic FEA (model 1)	Casing bearing seats
3	Reaction Torque	Based on % of motor torque and gearbox reduction ratio	About axis of output shaft

Model 1: Determination of bearing loads. In this first part of the analysis, the load carrying internal components' assembly (comprised of shafts and gears) is imported to the FEA environment from 3D CAD format. This assembly excludes the casing parts, as shown in Figure 7. The goal is to calculate the loads imposed in the gearbox system by the motor running at full load condition.

Relative positions of all parts are exactly similar when assembled in the casing. The bearing load locations shown in Figure 7 are constrained radially to calculate the loads imposed by gearing movements. While setting up the model, each reduction stage is assigned with its respective rotational speeds, named as initial velocities. For example, initial velocity of high speed shaft (HSS) is 1,800 rpm; whereas the intermediate shaft runs at 180 rpm. In order to induce motion into the model, the HSS is forced to rotate at continuous speed of 1 revolution in 0.033 seconds (defined as 'prescribed displacement'). The simulation duration is set for 3 complete rotations of the HSS. The contacts (surface-to-surface) are defined between gears (hypoid pinion & gear, and intermediate shaft and spur gear) to transmit the motion from one stage to another. For precise gear engagement, the fine meshing is assigned at contact surfaces. To depict full load condition, full load torque is applied on the low speed shaft (LSS).

Model 2: FEA of stainless steel parts' assembly. In the second part of the simulation, bearing loads calculated in model 1 are applied to the bearing seats of the housing components which are held together by fasteners. The calculated bearing load is a vector quantity; therefore, all loads are assigned in specific directions.

Flange, or face mounted reducer is identified as a critical load case in which the maximum loading is shared by the housing components and the bolts (Fig. 6A). Figure 8 and Table 8 elaborate the load locations and magnitudes.

The following assumptions are considered while building this model set-up:

1. The bearing load is applied in parabolic distribution on the cylindrical surface of the bearing seats.
2. Coefficient of friction between all mating surfaces, including bolt threads is 0.2.
3. CF8 (cast steel) and wrought stainless steel are defined as isotropic materials.
4. The model simulates static analysis with utilization of bearing load calculated from dynamic simulation.
5. Bolts are preloaded before applying the loads from Table 8; the preloading values are determined based on the proof stress.

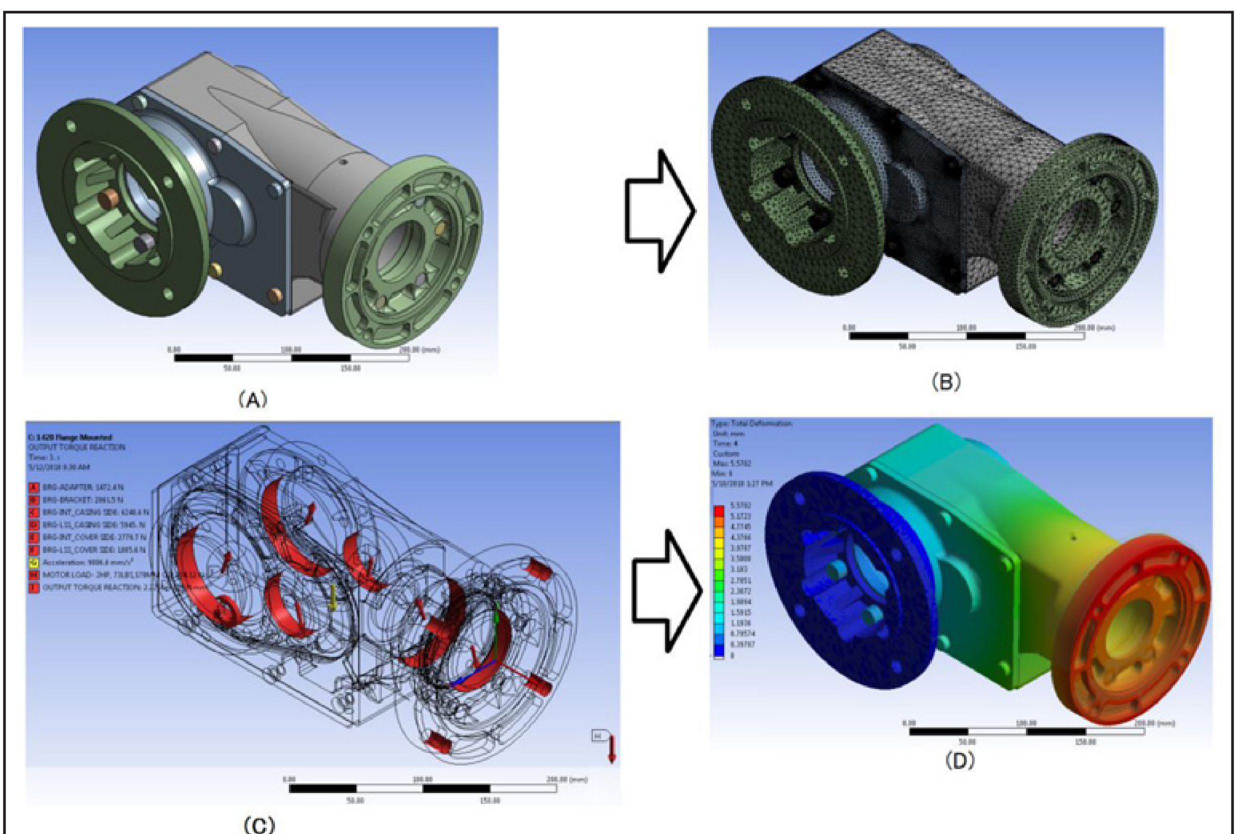


Figure 9 Finite Element Analysis Flow: (A) Geometry cleaning, (B) Meshing, (C) Loading, (D) Simulation.

6. For flange mount condition, only face bolt holes constrained in all degrees of freedom ('fixed').

Frictional contact between mating surfaces makes the model non-linear. The complete model is formulated with 1,188,563 nodes and 539,528 three-dimensional elements (SOLID186, SOLID187) (Ref. 15). The mesh density is optimized to alleviate its effect on the variation of result values within 5%.Figure 9 shows the FEA details and general sequence of the model building.

After running simulations, results are analyzed for higher stresses and displacements. The size of the cover bolts is selected such that the bolts would sustain the motor weight, the gearbox weight, and the bearing loads generated from at least 250% of motor torque. In other words, the mentioned loads would not overcome the clamping forces of the bolts.

Selection of other features. In reference to Table 6, output shaft material, output seal type, lubricant, shielded bearing lubricant, nameplate and plug are substituted. The output seal is substituted with cassette type seal which comprises of a two-piece metal stainless steel metal case (Fig. 10). This type of radial seal provides better resistance in washdown applications.

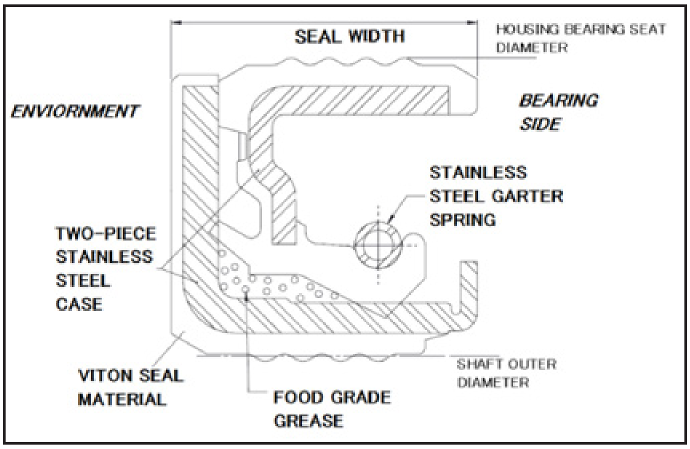


Figure 10 Cassette-type radial oil seal.

Table 9 Lubricant and maximum housing surface temperature comparisons

Temperatures	Unit 1 (Lowest ratio)		Unit 2 (Highest ratio)	
	Aluminum	Stainless	Aluminum	Stainless
Ambient	20	20	20	20
Housing surface (max. temperature area)	59.5	65.9	47.5	57

(in deg. Celsius)

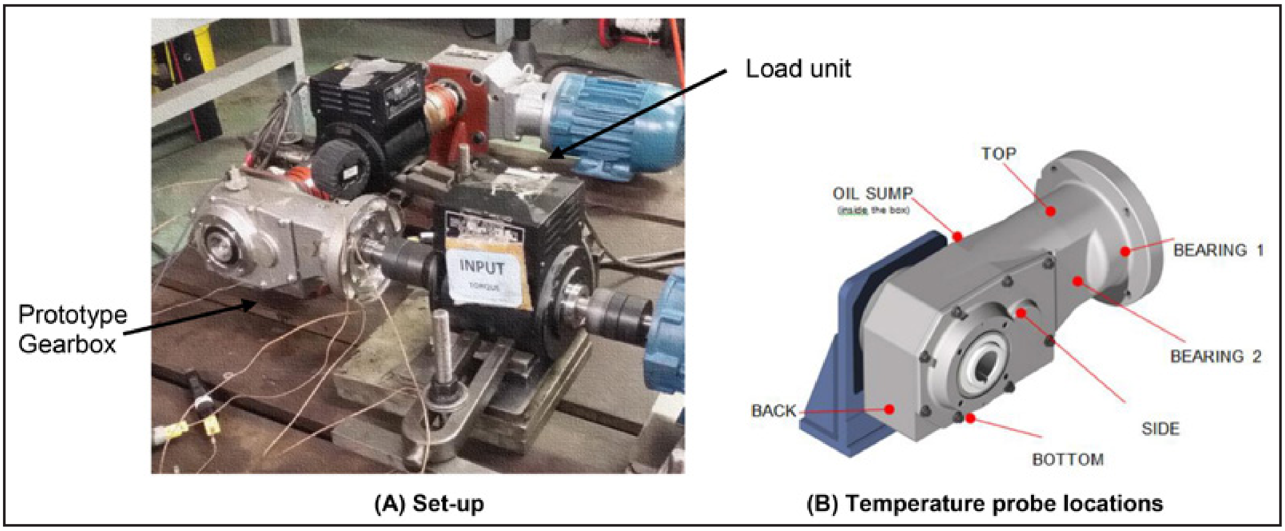


Figure 11 Prototype test setup.

Table 10 Process FMEA for Oil slinger assembly

Assembly Sequence #	Process Function	Potential Failure Mode	Effect of Failure	Severity
1	Install High speed shaft subassembly	none		
2	Heat oil slinger with Torch	none		
3	Slide the slinger on the subassembly from casing side opening	Cannot slide as it loses the heat before installation. Difficulty in installation.	**Process Effect:** Longer assembly TAKT time. Improper installation. **Product Effect:** Lubricant leakage	8
4	Install snap ring using pliers	Cannot access snap ring with pliers	**Process Effect:** Longer assembly TAKT time. Improper installation. **Product Effect:** loosening of oil slinger when product is in operation	9

As the lubricant effect gearbox lubricant changes from standard to the food grade-compliant, one has conducted physical testing to evaluate the lubricant's suitability for gears, bearings and overall temperature.

Physical Prototype Testing

Surface temperature validation of the gearbox housing has been determined as a primary purpose of performing physical prototype testing. Additionally, assembly validation, influence of cleaning and sanitizing chemical (used in wash-down applications) and field testing are other items achieved from the prototype (Fig. 11). Product is finalized after second iteration of the physical prototype. Salt spray test and ingress protection tests are also followed.

Product Development Phase III

Digital and physical prototypes are iterated and finalized in the previous development phase. This phase focuses on qualifying the final prototype parts for production and assembly. Process FMEA is utilized to identify and act on the potential failures originated from the parts' manufacturing and product assembly.

As an example, the change from four-piece casing design to three-piece design is required to validate the existing assembly process. With FMEA (Table 10) and Figure 12, the paper illustrates the changes made in Oil slinger design and assembly for the ease of installation and assembly TAKT time improvement.

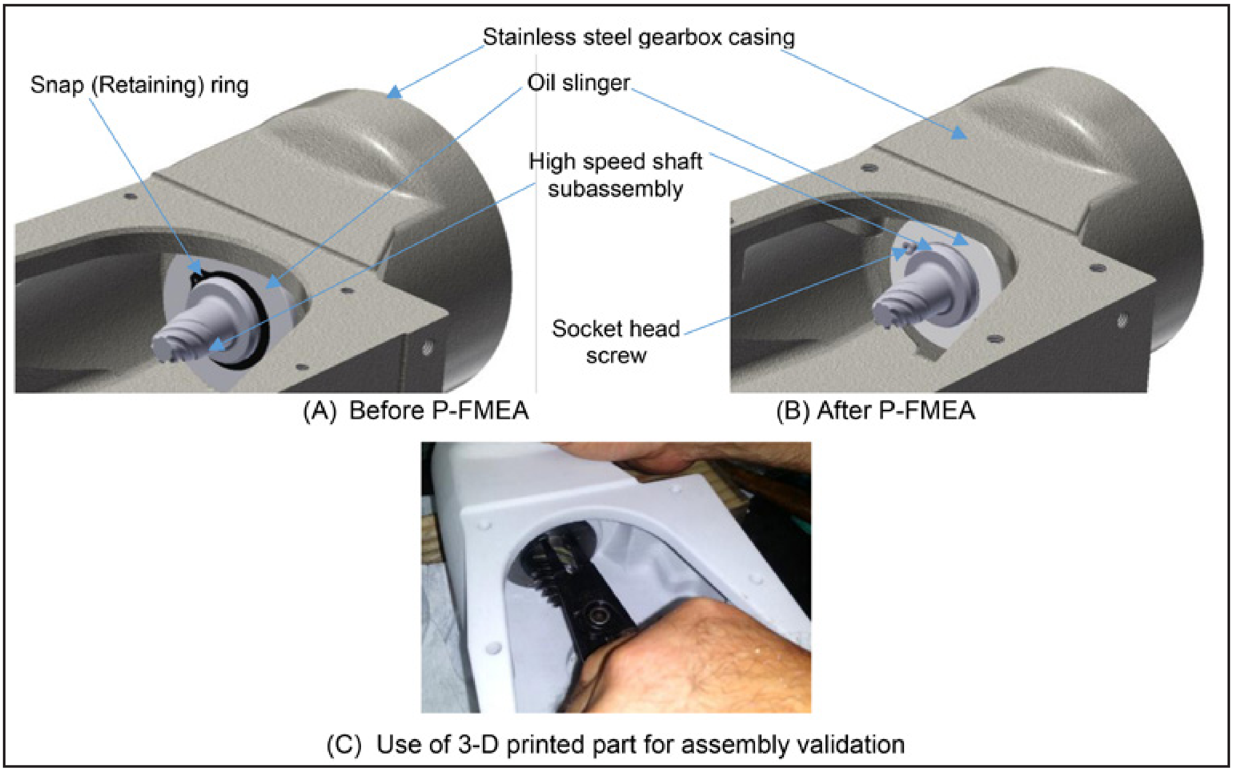


Figure 12 Change in oil slinger design after executing process FMEA.

Potential Cause(s) of Failure	Occurrence	Current design control (Prevention)	Current design control (Detection)	Detection	RPN	Recommended Actions
It takes too long to access the subassembly, because of narrow gap in casing opening	7	none	Visual check TAKT time count	9	504	1. Change oil slinger design, introduce clearance fit to eliminate the need for heating process. 2. Introduce screw installation
Not enough casing opening to use pliers	8	none	Visual check TAKT time count	9	648	1. Eliminate snap ring from the assembly 2. Introduce screw installation 3. Change Casing design to create bigger casing opening

Conclusion

Product redesign of an existing gearbox is performed in an efficient product development environment in order to meet food and beverage industry requirements. Effective use of the integration of QFD and FMEA tools in a redesign process is demonstrated in the paper. These tools have facilitated decision making, technical prioritization and potential failure elimination processes.

Finite element analysis and 3-D printing tools are utilized to accelerate the product development process through different phases. These tools have helped to keep the physical prototypes and their testing as minimal as possible. Gearbox housing design is iterated and validated to meet structural, thermal, and cleaning/sanitization requirements. The design iterations are also checked for process and assembly before making physical prototypes. The laboratory tests, such as IP69K and salt spray test are carried out to confirm the ingress protection and surface consistency confirm corrosion resistance, respectively. **PTE**

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