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PRODUCT ROBUSTNESS PHILOSOPHY – A STRATEGY TOWARDS ZERO VARIATION MANUFACTURING (ZVM)

Murthy S. Boorla, Tobias Eifler, Chris McMahon, Thomas J. Howard

Technical University of Denmark, Department of Mechanical Engineering, Denmark

Corresponding author:
S.M. Boorla
Engineering Design and Product Development Section
Mechanical Engineering
Denmark Technical University
2800 Kgs. Lyngby, Denmark
phone: (+45) 45256250
e-mail: srimbo@mek.dtu.dk

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Abstract
A product is referred to as robust when its performance is consistent. In current product robustness paradigms, robustness is the responsibility of engineering design. Drawings and 3D models should be released to manufacturing after applying all the possible robust design principles. But there are no methods referred for manufacturing to carry and improve product robustness after the design freeze. This paper proposes a process of inducing product robustness at all stages of product development from design release to the start of mass production. A manufacturing strategy of absorbing all obvious variations and an approach of turning variations to cancel one another are defined. Verified the application feasibility and established the robustness quantification method at each stage. The theoretical and actual sensitivity of different parameters is identified as indicators. Theoretical and actual performance variation and accuracy of estimation are established as robustness metric. Manufacturing plan alignment to design, complimenting the design and process sensitivities, countering process mean shifts with tool deviations, higher adjustable assembly tools are enablers to achieve product robustness.

Keywords
product robustness, variation absorption, product maturation, zero variation manufacturing, Industry 4.0, production readiness.

Introduction

Product robustness indicates minimum variation in performance through all internal and external variations [1]. There are many established robust design methods available for ensuring the robustness at design stage [2–4] focusing on eliminating contributors to variation or reducing the design's sensitivity to their effects. There also exist several approaches for monitoring and estimating robustness in mass production by combining the functional relationship derived at product design stage with actual measurement data [5–7]. But very few publications may be found focusing on methods and opportunities for achieving robustness during the manufacturing planning and tools and equipment development stages. For example, Anil Mital [8] recommends the establishment of transformation relationships between product features and process features and further process variables in manufacturing planning to achieving high product performance in terms of robustness. To overcome this limitation, a generic new product development process from "Design freeze" to "Start of production", shown in Fig. 1 is proposed to highlight the "Product trials and maturation phase" currently neglected in product robustness philosophy.

In the present robust design paradigm, it is considered that the achievement of product robustness is concluded at engineering design. Further, the manufacturing role is only to adhere to the drawings and other product specifications released by the design

team. This understanding makes manufacturing verify its performance against the design achievement. Figure 2 shows a hypothetical injection device to describe typically how a manufacturing quality metric is arrived at.

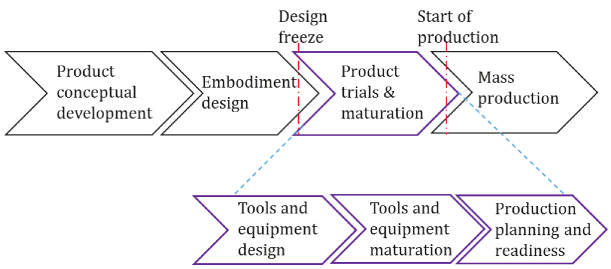

Fig. 1. The product trials and maturation phase, within the product development process.

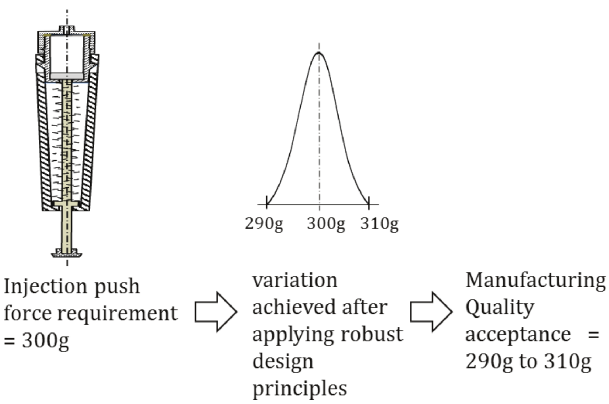

Fig. 2. Generic process of fixing manufacturing quality target values.

Once the target is given, manufacturing is driven to achieve this and all the products found within the specified range are accepted and considered to be the same qualitative performance. This approach limits the possibility of manufacturing adding more robustness to the product. The research described in this paper explored the opportunities for continuing the robustness considerations in manufacturing, after engineering design release.

The remainder of the paper is organized as follows. First of all, Motivation section describes the gap in current industry practice. Method section detailed about the approach followed in the research. ZVM approach at various stages of manufacturing and the metric at each is discussed in Results and Discussion section. Paper closes with a ZVM significance and implementation challenges in Conclusions.

Motivation

Taguchi's [9] robustness theories are well appreciated by the industry [10]. According to Taguchi every product that deviates from its nominal performance has a loss in value. He developed a quality loss function to quantify the loss as proportionate to the deviation. Figure 3 shows the difference of traditional and Taguchi's quality approach.

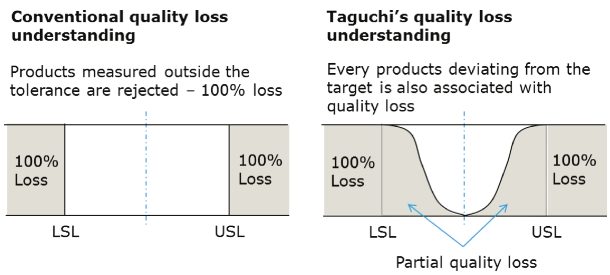

Fig. 3. Traditional and Taguchi loss function compared.

In traditional understanding of quality, no action is required during production for the products that fall within tolerance limits. In case of Taguchi's proposal every product that moves away from target needs a correction. The traditional quality approach measures the production performance in a number of defects/rejections. In Taguchi's approach, production performance measured in terms of loss occurring due to product variation from the target. The traditional quality approach has matured over decades, and industry is able to practice Zero Defect Manufacturing (ZDM) [11, 12], but not yet enabled us to reach to Zero Variation Manufacturing (ZVM). The research reported here has focused on the process of identifying and providing opportunities to shift the product to target whenever it deviates in mass production, which can, in turn, further the aim of achieving ZVM.

When manufacturing aims to consistently produce the target product performance representing the customer's needs, their focus needs to be on the end product performance, not on the performance of its independent parts. Thus a 'manufacture for robustness' strategy may differ greatly from a regular 'manufacture for quality' strategy of the current paradigm.

Product robustness strategy proposed: When the variation is obvious in manufacturing, also absorb before it reaches the customer.

The approach required for absorption: Build favourable situation for nullifying the effect of one variation with another, instead of them cumulating.

Figure 4 shows the simplistic representation of the product development cycle where design and manufacturing meet the customer intent by producing the performance exact, such as total length T in Fig. 4. Even if the design provided tolerances of x, y and z for respective part dimensions, manufactur-

ing can still aim towards zero variation by ensuring all those variations together equate to zero, such as $\pm x \pm y \pm z = 0$ shown in the Fig. 4 This is applicable to every type of performance and variation.

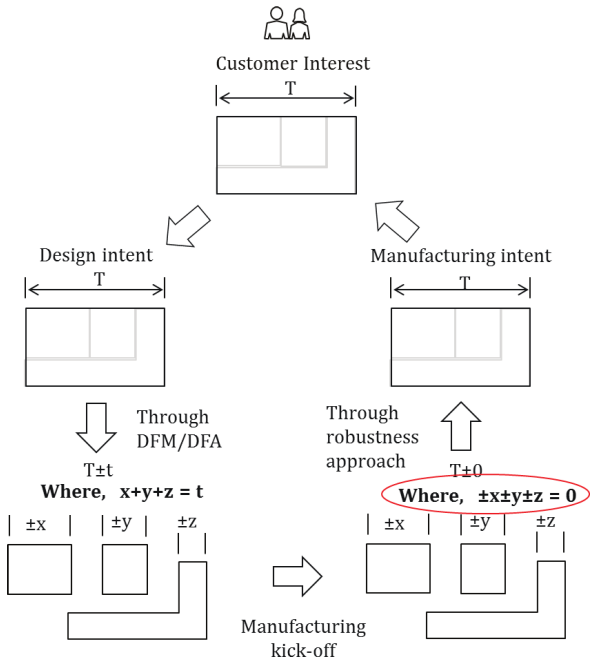

Fig. 4. A manufacturing strategy and approach, where all the variations are nullified within the factory and provide the product at the nominal performance to customer.

Designer aims for the product performance best suit to the customer and gets compromised with manufacturing limitation [13], demands designer to provide tolerances for each design parameter while passing through Design For Manufacturing and Assembly (DFM/DFA). This results in an undesired variation in final product performance. The proposed strategy aimed to nullify the manufacturing generated variation within the factory and pass the designer intended performance to the customer. It aligns with Taguchi's product robustness definition "A product said to be functionally robust if it inherently tends to diminish the effects of input variation on its performance" [14].

Method

In the robustness-focused approach, achieving the target for all products produced is the manufacturing objective. This is possible only when we know the variation status of the product at every stage of its manufacturing and use this knowledge to ensure that net variation is zero. The method followed in this research, shown in Fig. 5 involves asking questions at each stage and finding possible answers.

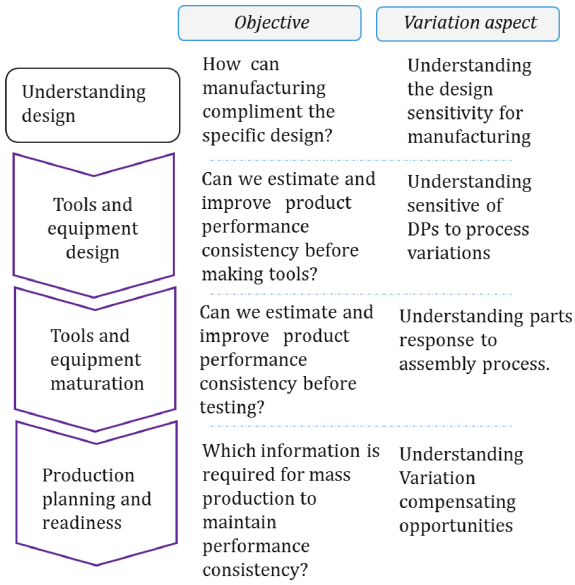

Fig. 5. An approach of questioning at each stage for developing the process.

Understanding the design

The aim of manufacturing is to bring the digital aspiration of the designer into reality. Many arguments and recommendations are made [15, 16] regarding information flow requirements from design to manufacturing in order to overcome the communication gaps. Not only Design Parameter (DP) variation, but also their influence on Functional Performance (FP) and interactions with other DPs are required. This enables manufacturing to plan its efforts towards the achievement of DPs according to the degree of their influence individually and together on product performance. Understanding the condition of multiple DPs coupled to multiple FPs (axiomatic) [17] directs manufacturing to balance the design parameters across various targets. Manufacturing can link the design understanding to their plan as in Table 1.

Table 1
Aspects of design influence on manufacturing planning.

Design philosophy	Link to Manufacturing planning
Sensitivity	Higher sensitivity DPs can be managed with precise and adjustable process.
DP interaction	Interactive DPs may need to vary together and control them as one set of parameters.
Axiomatic conditions	Higher coupled DPs need to be precise, so that common ground is stable. Make them earliest, so that other DPs can be made according.

When a product performance is highly sensitive to certain DPs, those become major contributors for

performance drift. Manufacturing should plan the process to be more flexible so that DPs can be adjusted quickly to bring the performance back to the position. Figure 6 shows a cylinder length between two collars as a critical DP. Option 2 may give higher control on DP, in turn on FP.

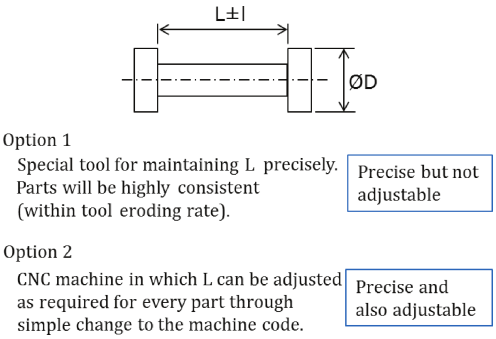

Fig. 6. Design parameter L considered highly critical to the function.

When certain DPs are changing their behaviour relative to others demands all of them to be seen together. Manufacturing needs to plan monitoring and control of all of them as one set, which will help to manage their variations together, instead of individually. For example, for the snap in the Fig. 7, its final performance is determined by its engaging force. The associated DPs are highly coupled through their relationship equation. A manufacturing plan for producing both the parts and also assembling them at the same place could enable the team to adjust, controllable parameters to compensate the effect of, previously induced variation in the product aiming for the desired engagement force. In this example assembly dimension "d" and "i" may be adjusted according to the "part 1" dimensions "b, t, θ" shown in Fig. 7 and its material property "E".

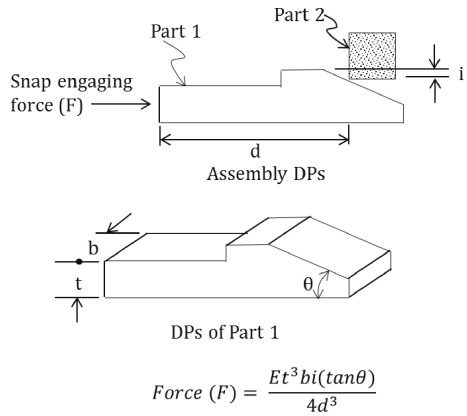

Fig. 7. Design parameters of the parts and assembly are highly interacting towards engaging force.

Some DPs may contribute to more than one FP (known as functional coupling), which limits the DP flexibility. Manufacturing needs to ensure the most precise process is used for producing those DPs. To compensate for the variation effect of these coupled DPs, the uncoupled DPs can be adjusted. This asks manufacturing to look for opportunities to produce coupled DPs first and uncoupled DPs later to allow them to be adjusted accordingly. Table 2 shows a scenario of design information of an injection device with 17 DPs together achieving five FPs. Uncoupled DPs of all FPs are highlighted.

Table 2
The axiomatic situation of design is a key input for manufacturing plan.

Parts --→	DPs	Product specification --→		FP1 Overall length 106 ± 1.1 mm	FP2 Push button force 1.5 ± 0.37 N	FP3 Filling capacity 1844 ± 114 ml	FP4 Gap 2 ± 0.6 mm	FP5 Gap uniformity 0 ± 0.3
		Nominal	Tol	contribution	contribution	contribution	contribution	contribution
Housing	DP1	59	±0.5	15.9%	20.0%			
	DP2	2	±0.3	9.5%	12.0%			
	DP3	5	±0.2	6.3%	8.0%		14.8%	40.0%
Barrel	DP4	28	±0.5	15.9%		22.3%	37.0%	
	DP5	10	±0.3	9.5%	12.0%		22.2%	
	DP6	8	±0.2					40.0%
	DP7	∅ 10	±0.3			60.0%		
	DP8	1.5	±0.2			8.9%		
Piston	DP9	3	±0.2			8.9%		
Cap	DP10	12	±0.5	15.9%				
	DP11	9	±0.2	6.3%			14.8%	
	DP12	3	±0.1				7.4%	20.0%
Push rod	DP13	2	±0.2		8.0%			
	DP14	30	±0.3	9.5%				
Button	DP15	2	±0.3	9.5%				
Spring	DP16	45	±1		40.0%			
Seal	DP17	1	±0.05	1.6%			3.7%	

Coupled DPs are to be precise and uncoupled DP to be focused for adjustability. For example, FP1 has three uncoupled DPs to adjust and maintain. FP5 is having only one uncoupled DP and FP4 does not have one. These to be identified as critical for robustness. Time hierarchy of the production to be aligned to this criticality to utilize the uncoupled DP adjustments. In this example, producing "Housing and Seal" first, "Cap and Barrel" next and Piston, Button, Push rod and Spring" later.

This table also gives inputs to next stage of product development. FP3 and FP5's uncoupled DPs are belonged to one part, Barrel. This means Barrel production process should aim to provide independent control of different DPs within one manufacturing set, in the Barrel case, a plastic moulding tool and injection process control.

Production capability needs to be calculated on the basis of product performances variation, not on DPs variation. A manufacturing plan focused on product robustness will attempt to achieve minimum product performance variation by countering high sensitivity, interactions and axiomatic conditions with suitable process selection, control mechanisms and adjustability.

Equipment design

Once 3D models, part specifications and the assembly process are defined, manufacturing begins the tools and fixtures design. Those may be injection moulds, pressing dies, welding fixtures, etc. In the present digital world, every design is virtually simulated and verified. Figure 8 shows the position of tools/fixtures design in the variation flow path from process to final performance.

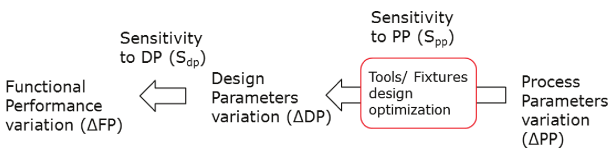

Fig. 8. Variation flow from the production process to the final product.

Tool design optimization ensures that a DP's sensitivity to a PP (Spp) is as low as possible so that part DPs are less varied during production. However, some sensitivities will inevitably be higher than others. Design optimization should ensure that Spp is as low as possible for the DPs that have a high FP sensitivity (Sdp). The robustness achieved through tool design can be quantified using Eq. (1)

$$\Delta FP = \Delta PP\ S_{pp}\ S_{dp}. \tag{1}$$

Functional performance variation is the result of PP variation factored by both sensitivities.

This allows for estimating product robustness at the equipment design stage. While designing tools, this is needed to compliment the next stage by providing scope for maturation [16]. The tool design strategy needs to consider critical DPs with easy adjustability in the tool, allowing optimization of the physical tool. Figure 9 shows a plastic part with a critical hole diameter (Ød). Designing the mould with a changeable insert to achieve the critical diameter allows for fine tuning the mould by replacing either a smaller or bigger size according to the final shrinkage achieved.

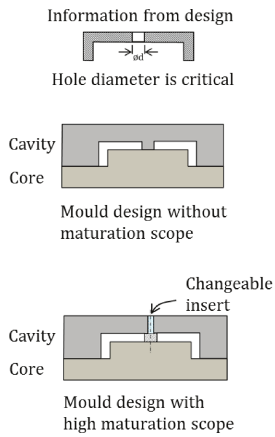

Fig. 9. Higher tool maturation with changeable insert for achieving critical hole diameter.

Similarly, assembly fixtures need adjustment for better joint performance and to fulfil assembly Dimensional Targets (DT) such as achieving length A in Fig. 10. The figure shows an example of welding

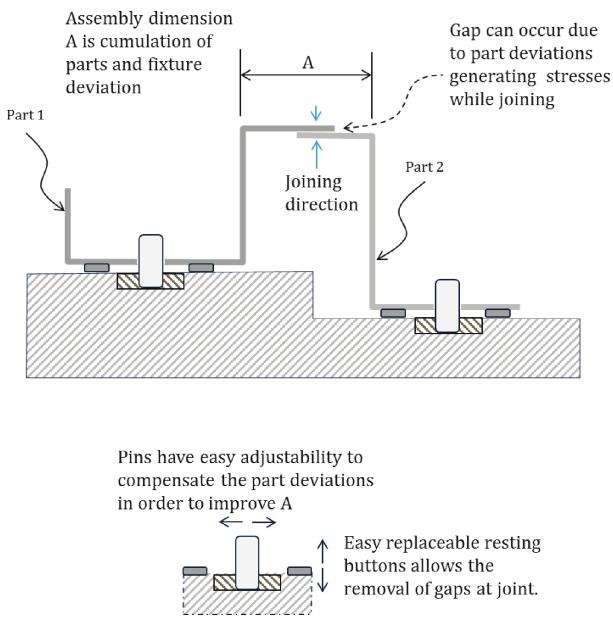

Fig. 10. A sheet metal welding fixture design needs maturation scope.

fixture where the critical dimension of the assembly (A) is determined by both parts and fixture dimensions.

Equipment design should aim to ensure that critical dimensions can be achieved through tool maturation and that uncoupled DPs are adjustable for improvements. Adjustability is aimed to counter the impact of part and process variation.

Equipment readiness

An organization focused on product robustness would aim for zero product performance variation. This means parts variation, fixtures variation and impact of assembly process nullify one another and achieve zero variation on product performance. A meticulous understanding of each variation and its contribution is required to achieve robustness. Every discrete assembly manufactured product passes through a part and process maturation stage before starting mass production [18, 19]. Part manufacturing tools (plastic moulds, press dies, casting dies, etc.) are assessed for accuracy achieved through machining and their response to the manufacturing process (moulding, pressing, casting, etc.). Figure 11 shows the stages of a plastic part making and the acceptance process. Tool contribution (Tc), and Process contribution (Pc) are added at these stages to the part to vary.

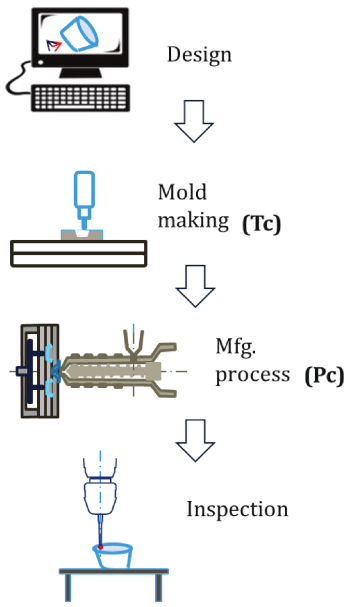

Fig. 11. An injection moulding part making and acceptance process.

The traditional part approval process only checks that the final measured part dimensions are within tolerance, which is the result of variations Tc and Pc, together. For a robust product, one needs to understand these components of variation independently, so that improvement actions can be specific.

Tc: Tool making process contains several steps including, machining, heat treatment, polishing, assembly, etc. Deviations on these steel/metal tools are proportionate to their size and complexity. Mould tool inspection generally checks the deviations from its nominal position, which does not give the part dimension effect accurately. To understand the tool impact on parts, one needs to verify the moulding tool against the part dimensions controlled in the drawing. Figure 12 exemplifies a moulding tool measurement in both methods.

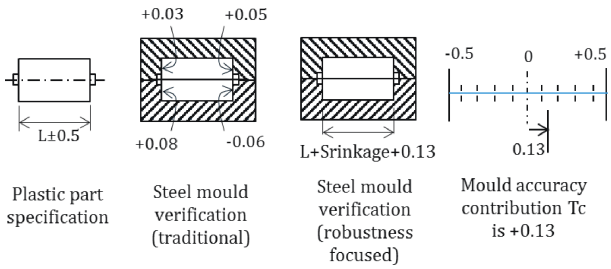

Fig. 12. Understanding mould accuracy contribution.

When the tool is aimed to be within 0.1, the mould is considered to be good in traditional understanding. This deviation is directly linked to the variation seen in the DP which has a total tolerance of ±0.5. Thus the tool accuracy is responsible for 0.13 (roughly 25%) of it. This deviation is obvious to every part comes from the mould (mould's long run deterioration is neglected in this discussion for simplification).

Pc: The mould designer specifies the best suited PPs (injection pressure, mould temperature, cooling rate, etc.), for that mould layout for that specific plastic raw material. The designer also simulates and verify the virtual tool in the digital environment and confirm these PPs. The intent of physical tool trials is to verify the same in reality. After trials, the best set of PPs is updated, at which point parts from the tool are consistent. Trials also include variations in PPs that are expected during long run mass production and capture the part deviations. Figure 13 shows the example of capturing process contribution over tool trials, in continuation of Fig. 12 example.

This detailed variation component analysis approach brings meticulous understanding about the part position and allows for establishing sensitivity values of DPs to their PPs. This also clarifies that the process control can improve the part within Pc range only.

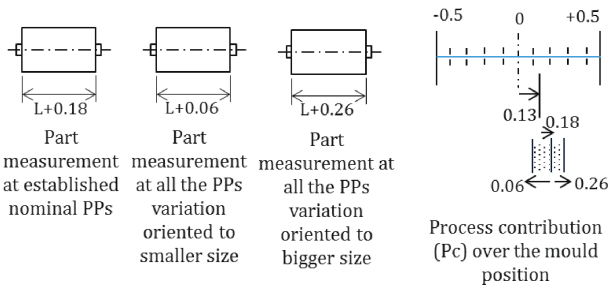

Fig. 13. Process influence is over and above the tool position, not on CAD nominal.

After parts and assembly fixtures are independently verified, their response to assembly process is to be confirmed for final product performance. Along with parts and fixtures deviations, assembly processes may induce stresses, in turn additional deviations. Assembly trials with the known part and fixture deviations give assembly process contribution and also direct actions required for nullifying variations. The nature of the improvements leads to the types of actions. Fixture changes are easy, quick and certain, and are applied immediately to all the units. Tool (moulds/die, etc) changes are certain, timeconsuming and often non-reversible.

Welding of sheet metal parts discussed in Fig. 10 with maturation scope induced allows nullifying the variations as shown in Fig. 14. Adjustment of fixture pins by 0.4 compensates their own and the part deviations and brings A to nominal.

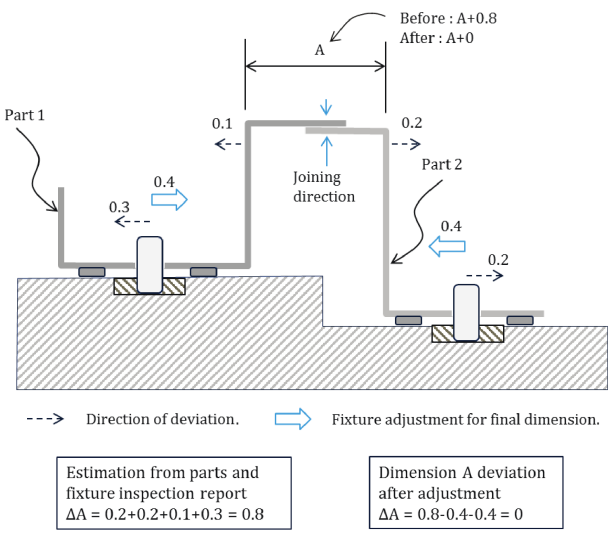

Fig. 14. Assembly achievement is a combination of parts and fixture variations.

At this stage, all the fixed deviations and potential process impacts are well known for estimating final product performance and opportunities along the production process, to shift performance to nominal.

SOP readiness:

An intelligent equipment design, accurate manufacturing and performance focused maturation lead to predictable production. An accurate relationship matrix of DPs and PPs continuing the information received from design is required for performance estimation. Figure 15 shows the representative product information flow extended from design over equipment design, tool trials and maturation. This detailed matrix allows prediction of the product performance when all PP data are known.

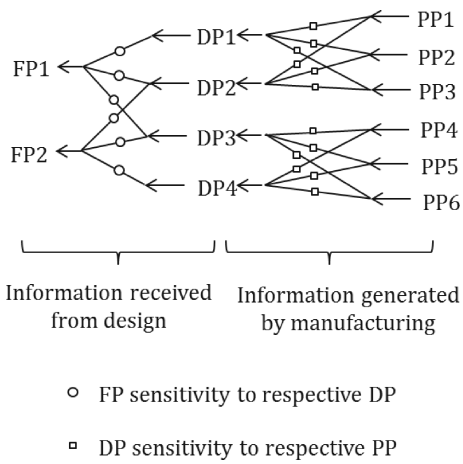

Fig. 15. Relationship of product performances linking to operational PPs.

To be able to predict random unit from the production line, a measurement plan needs to be aligned to the production plan. To estimate the performance of any product picked from the end of the assembly line, one has to know the measurements of each part of the same assembly. Assembly lines of mass production work on different logistic principles; for example in a Just In Sequence (JIS) system, parts from manufacturing units reach the assembly line in the same sequence as the assembly plan. In this system, part measurements happen at the part manufacturing locations only, often the case in global product development when parts are manufactured overseas. Measurement data captured at various locations of the units on current assembly line are to be seen together. Figure 16 shows the generic assembly flow diagram with part logistics for a 5 part assembly product.

The current product from assembly line contains DPs shown in their respective measurement reports, x, y, z, a and b. Performance estimation of that assembly with these parts needs to be calculated with the same values. Parts inspection data capturing and feeding process is required to align the assembling plan. Every part may not get measured, but every

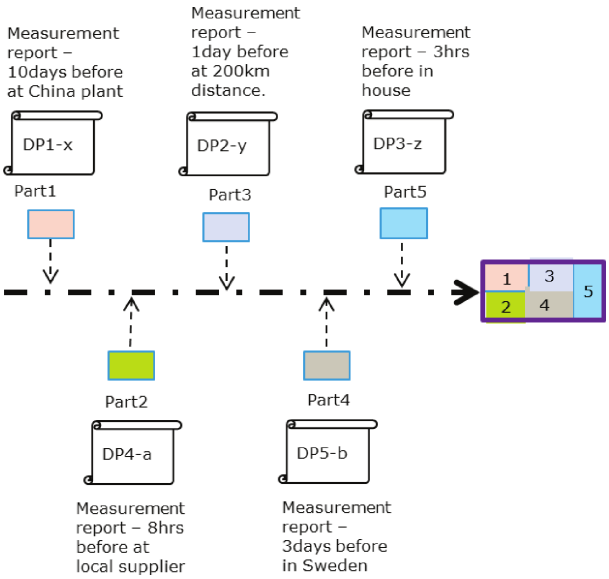

Fig. 16. Parts getting assembled are measured at different times, DP inputs to the robustness monitoring system need to follow the same assembly plan, to allow prediction of the FPs of that assembly.

batch received in the assembly line is represented by a measurement report, applied to all the parts in that batch. This situation demands to keep the variation limits for the batch. This allows the production team to know the robustness achieved and gives an opportunity to compensate through assembly variables for functional performance consistency. Readiness for mass production can be summarised as:

- establishing a manufacturing and assembly processes with accurate sensitivity values of all variables to performances;
- a prediction model linking the relationships between process parameters to performances, which is aligned to the production plan;
- adjustability opportunities for each FP.

Additionally, cost and time aspects of each adjustability allow for selecting the quickest and fastest solution for improvements. Integrating this information flow to overall organizational monitoring system [20] quickens the decision making.

Results and discussion

In the process of finding answers to the questions (Fig. 5) of all possible opportunities for achieving zero net performance variation are explored at each stage of product trials and maturation (Fig. 1). Estimating final product performance at each stage is found feasible with established sensitives to variables. The contribution of each stage can be understood with robustness indicators, which are the base for final achievement. Table 3 shows the summarized robustness indicators, metric and enablers for each stage.

This manufacturing strategy builds ability for production to shift the product performance to its target whenever drifts occur, proactively by prediction. An aligned measurement system of PPs and DPs make it possible to estimate the performance of a product at any assembly stage without testing. All stages of development are focused not only on reducing the variation also on providing opportunities for adjusting parameters against uncontrolled variations. When a production system contains adjustability higher than the variables effect and they are agile to meet mass production cycle time, that leads to ZVM.

The basic principle of this manufacturing strategy proposal is "knowing meticulous details of the product performance mechanism" and "adjust the right lever" for the desired improvement, which is also base for Howard's [21] proposal of Variation Management Framework (VMF). Production strategies on similar principles are more visible in process manufacturing products [22,23] in which automation is the main driver.

The manufacturing strategy and approach for robust products starts with the information flow from the product design team, and thus demands that the design team prepare their information accordingly.

Capturing accurate sensitivity values is a process of extensive experiments at the virtual and physical stage of development. Changing present quality understanding at all levels of manufacturing function and at suppliers is a challenge.

ZVM achievement is directly proportionate to the accuracy of sensitivity values established over the development. Two elements are still contributing to final product unnoticed.

1. batch accuracy: ZVM needs 100% measurement. The concept of sampling is a compromise;
2. total uncertainty: Measurement uncertainty, adjustability action uncertainty, operator skill difference etc.

Organizations need to ensure that above variation contribution together is lesser than customer perceivable variation limit. This keeps the user experience consistant

Table 3
Summary of robustness focused approach.

	Understanding design philosophy	Equipment (Tools&fixtures) design (digital)	Equipment (Tools&fixtures) readiness (physical)	Production readiness
Robustness indicators	Theoretical FP sensitivity to DPs (θ)	1. Theoretical DP sensitivity to PPs (θ) 2. Theoretical DP sensitivity to DTs (θ)	1. Actual FP sensitivity to DPs (θ) 2. Actual DP sensitivity to DTs (θ) 3. Actual DP sensitivity to PPs	1.Batch accuracy in % 2. Time and cost parameters of adjustability in sec and $
Robustness metric	Theoretical FP variation through DPs	Theoretical FP variation through PPs, DPs and DTs	Actual FP variation through PPs, DPs and DTs	1. Accuracy of FP variation estimation 2. Ability to calculate and act for each FP improvement in production speed
Enablers	1.Manufacturing plan alignment with DPs sensitivity, interactions and axiomatic conditions	1.Critical DPs are less sensitive to PPs. 2. Higher maturation scope for critical DPs. 3. Tool measurement plan aligned to DPs	1.Tool deviations are favourable to process means. 2. Assembly tools are adjustable to compensate part deviations. 3.Total adjustability of each FP is more than its variables contribution	1.Higher batch accuracy irrespective to its accepted tolerance. 2. Inspection data processing alignment with production plan 3.Robustness monitoring system linking PPs to final product performance.

Conclusions

This ZVM strategy provides an early estimation of performance and also creates adjusting opportunities for maintaining zero variation. An established robustness metric and its indicators at every stage provide a grip on the product throughout the development process. This manufacturing strategy for robustness is applicable to any type of product and process. Higher measurement frequency leads to accurate estimation. Recent developments through the industry 4.0 revolution focused on proactive communications are demanding the manufacturing concepts for the same principle of adjustability [24–26]. ZVM strategy applied at product maturation stage (between design release and the start of production) provides opportunities to utilize Industry 4.0 infrastructure at mass production with accurate information of variables and their influence for effective use of adjustability. An accurate estimation system of the type proposed in this paper can be used to reduce the final product testing requirement.

Application of ZVM on mechanical assemblies and process manufacturing products to be examined visa-vis. Further research required in establishing the process of finding user perceivable range of product performances. The process of measuring production efficiency in terms of quality loss instead of a number of defects is required more studies.

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