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Industry 4.0 – A challenge for variation simulation tools for mechanical assemblies

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Abstract. Variation Analysis (VA) is used to simulate final product variation, taking into consideration part manufacturing and assembly variations. In VA, all the manufacturing and assembly processes are defined at the product design stage. Process Capability Data Bases (PCDB) provide information about measured variation from previous products and processes and allow the designer to apply this to the new product. A new challenge to this traditional approach is posed by the Industry 4.0 (I4.0) revolution, where Smart Manufacturing (SM) is applied. The manufacturing intelligence and adaptability characteristics of SM make present PCDBs obsolete. Current tolerance analysis methods, which are made for discrete assembly products, are also challenged. This paper discusses the differences expected in future factories relevant to VA, and the approaches required to meet this challenge. Current processes are mapped using I4.0 philosophy and gaps are analysed for potential approaches for tolerance analysis tools. Matching points of simulation capability and I4.0 intents are identified as opportunities. Applying conditional variations, incorporating levels of adjustability, and the un-suitability of present Monte Carlo simulation due to changed mass production characteristics, are considered as major challenges. Opportunities including predicting residual stresses in the final product and linking them to product deterioration, calculating non-dimensional performances and extending simulations for process manufactured products, such as drugs, food products etc. are additional winning aspects for next generation VA tools.

Keywords: industry 4.0, variation analysis, Monte Carlo, conditional variation, selective manufacturing

1. Introduction

The purpose of Variation Analysis (VA) is to simulate real-time production scenarios. VA takes variation in Design Parameters (DPs) as input and follows the assembly process to replicate production. VA tools are also often termed as Computer Aided Tolerancing (CAT) tools. They have been developed to include the nature of DP variations (for example the statistical distribution type) and also to allow DP values to be randomly varied to estimate the Functional Performance (FP) variation in long-term production. Monte Carlo simulation is considered a realistic replication of long run mass production (Arya *et al.* 2012, Yan *et al.* 2015). The designer depends on the Process Capability Database (PCDB), constructed from historic manufacturing and product data, for DP variations to understand final product variation using the simulation. Figure 1 shows the

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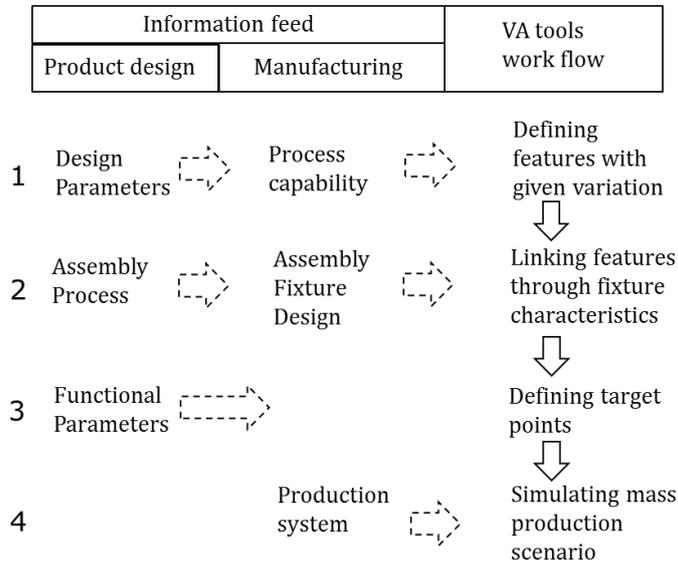


Fig. 1 Information flow from design and manufacturing to VA simulation workflow

information flow from product design and manufacturing as input to a typical VA work-flow.

In discrete assembly products, it is the practice that all DPs are maintained through quality control, it is expected that variation will follow the standard distribution (normal, lognormal, uniform, etc.). It is further considered that the assembly process parameters are independent of the DP status. This allows current VA tools (3DCS, VisVSA, CETOL, RD&T etc.) (Prisco and Giorleo 2002, Mikael *et al.* 2016) to follow in sequence the VA work-flow steps shown in Fig. 1.

The new industrial revolution Industry 4.0 (I4.0) has brought changes to these basic processes of discrete assembly production through Smart Manufacturing (SM) (Suri *et al.* 2017). This new revolution is based on processes with self-aware and self-adaptive characteristics (Dopico *et al.* 2016). In Fig. 2 a schematic representation showing differences to the current approach is presented.

Through for example the concept of Internet of Things (IoT), in I4.0 the parameter status at each stage is communicated to the next. Every station process may be self-adjusted according to the state of the previous station to meet final product function accuracy. A key opportunity in I4.0 is to absorb the variation passed by the previous station. This is expected to reduce the significance of variations at part level and also in assembly. This change challenges the current VA tool architecture, which is made for the current discrete assembly production process. Both the structure of information input and method of the simulation may need to be different for I4.0 production. This paper is focused on identifying such potential threats and discusses the possible solutions for future VA tools.

2. Method

The approach taken in the research was to map I4.0 characteristics onto the input information and process steps of a VA workflow (Fig. 1) to identify the challenges.

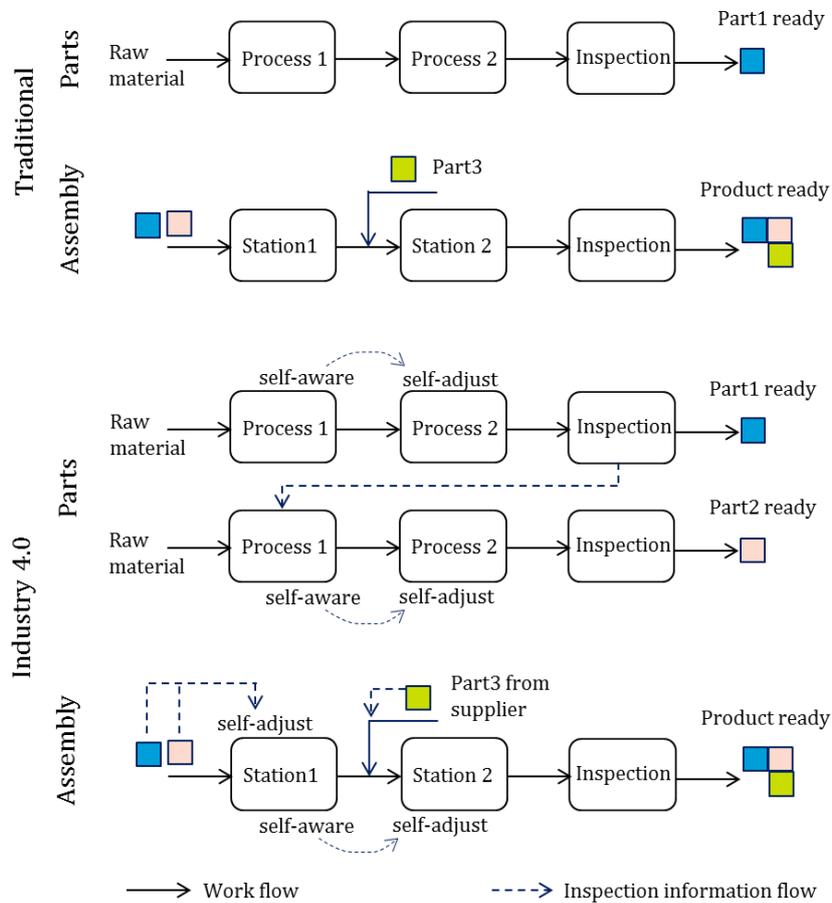


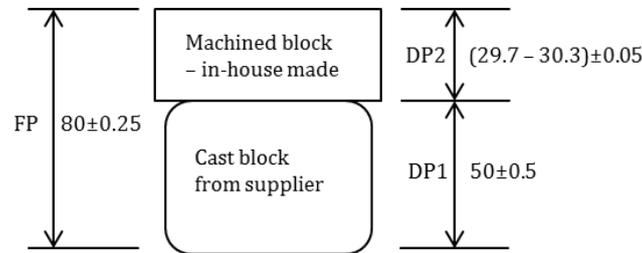
Fig. 2 Industry 4.0 is equipped with parameters status information flow (dashed arrows) from one stage to next

2.1 Design parameters with process capability

Manufacturing processes are expected to be highly automated with induced intelligence (Wang *et al.* 2016) in this new revolution. When numerical control systems were added in Industrial revolution 3, process capabilities were improved. For example, a metal block machined to its size improved its accuracy from $\pm 0.2\text{mm}$ to $\pm 0.05\text{mm}$ from conventional machine to CNC machine. But the changes expected in I4.0 are greater. Consider the example of a product with two blocks that need to maintain the total height of the two blocks together as performance. One block is sourced as a cast item without finishing and the other one is machined in-house with a possibility of closer tolerances as in Fig. 3.

Adaptive control systems (Bort *et al.* 2016) for CNC machines make them self-adjustable for the optimized machining process. This ability may be extended with more information feed to the machine for higher adaptability.

In the I4.0 scenario, an in-house CNC machining station is fed with the status of the incoming cast block size (between 49.5 and 50.5). The machine adjusts itself and makes the DP2 aiming to



Potential tolerancing method in I4.0 with mfg. input:
In-house CNC machine self-adjustability limit is ± 0.3

Fig. 3 Design communication possibilities in I4.0

compensate for casting variation as much as possible. Remaining casting variation and machining tolerance are passed to FP. The in-house machine adjustability (29.7-30.3) absorbed the portion of casting tolerance (up to 0.3); higher machine adjustability may absorb all the casting tolerance. Here the design information change is visible at DP2, with its conditional nominal value. Machining and casting tolerances from present PCDBs are not by themselves sufficient for VA in I4.0. VA tools need to accept not only variation (± 0.05) but also a possibility for change in the nominal as input. Here adjustability and accuracy may change for each machine. VA tools should provide a dedicated interface to manufacturing to provide their variation inputs for each production concept and optimize the adjustability options.

2.2 Assembly process with Assembly fixture design

There are two types of assemblies defined by Whitney (Whitney *et al.* 1999). I4.0 brings a third type of assembly with intelligent fixtures. The three together are:

Type 1: Assembly depends on part features;

Type 2: Assembly depends on fixture features; and

Type 3: Assembly depends on dynamically adjusted fixture features according to part features.

Even adaptive (Wan *et al.* 2017) and intelligent (Gonzalo *et al.* 2017) fixture system is not new, their application is expected to increase in I4.0 which influences the VA process. Fig. 4 shows the simplest part with its features referenced for least variation for hole position. In current traditional manufacturing, the longer side (A) is taken as a first datum, because that gives smaller variation in hole position compared to the shorter side (B) for the same waviness. However, this does not help when the real waviness effect of B is less than A. I4.0 gives the opportunity to switch the first datum either A or B dynamically according to whichever contributes least variation to hole position, with part geometry sensed every time, and with clamping follow the sensing.

VA tools fixture specification methods are required to be updated to allow such a conditional referencing system.

Assembly process parameters are also self-adjustable in I4.0 (Müller *et al.* 2016). For example, a sealant dispensing system cope part variability (Maiolino *et al.* 2017), the voltage for weld spot could be changed according to the part geometry to reduce distortions and stresses; tightening torque can be adjusted according to incoming spring constant to maintain uniform preload, and so on. VA tools should be able to take account of these capabilities as well in calculating the final product variation.

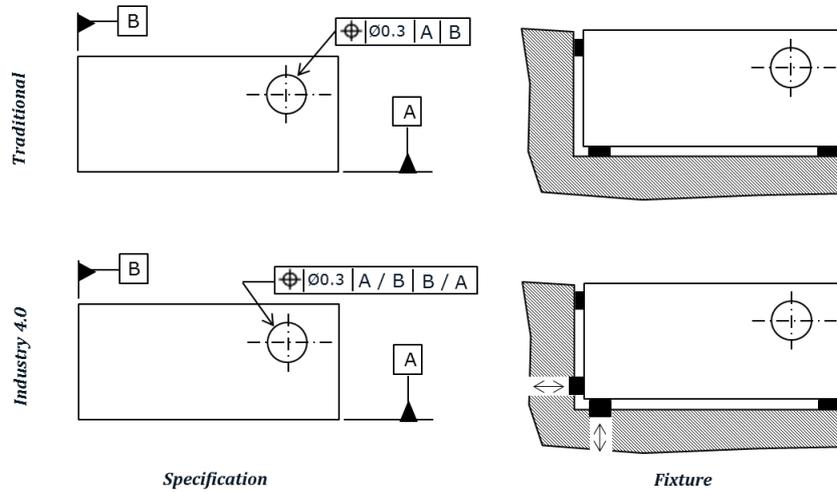


Fig. 4 Fixture design possibility with intelligence in I4.0. An adaptive fixture chooses the best possible reference every time according to the geometry arrived at

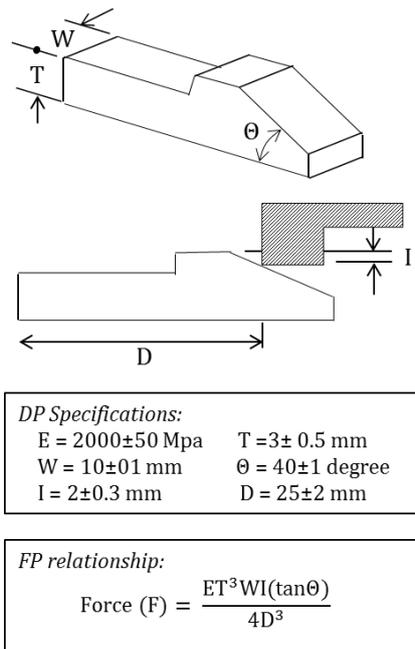


Fig. 5 A snap geometry DPs and their relationship with FP

2.3 Functional parameters – from product design

Often many measurements are performed to estimate the final product performance. A selected number of units only from production goes for testing to accept that batch. In the case of I4.0 testing (non-destructive) can be incorporated within the production line itself, meaning all the products are tested. For example, a cap engaging force through a plastic snap is one FP, shown in Fig. 5.

In traditional manufacturing individual snap dimension (T, W, and Θ) are maintained through part quality control and monitored and maintained assembly dimensions (I and D) through the assembly process. The force value (which is important FP) is typically not checked for every product but sampled from production. Current VA tools follow this production approach and estimate the assembly dimension variation but do not calculate the force value. In I4.0, however, every unit of production is tested by engaging the snap and noting the force and apply a possible adjustment for the desired force value. Product quality monitoring is through a collection of testing station data. This means variation simulation needs to estimate Force (F) variation.

Current VA tools are focused on accepting independent part dimensions and estimating assembly dimensions. VA tools architecture is made to accept only dimensional variations and results also only in dimensional variations. It matches well to traditional quality control methods, in which DP is monitored and maintained. In I4.0 VA tools need to take non-dimensional DPs (e.g. Young's Modulus of the material, E, in the snap example) as input and also the relationship equation of FP with its DPs such as F (Fig. 5).

2.4 Production system- from manufacturing

Mass production quality metrics have been based on standard deviation for many decades. Measuring the production ability in Six-sigma (Ferryanto 2007) is a well-accepted practice across the globe. Even if production systems are different (JIT, JIS, Manual, semi/fully automated, etc.) the six-sigma approach is found suitable. That has driven present VA tools to report their calculation results in a similar format. This probability-based approach is suitable when variables are random, but in the case of I4.0, variables may be conditional. Every variable may change its position according to the status of other previously manufactured variables. The present Monte-Carlo (Rubinstein and Kroese 2016) simulation does not reflect this new production approach. Even the basic probability theory of random variables does not work. Fig. 6 shows a random variables simulation and an I4.0 possibility, demonstrating the unsuitability.

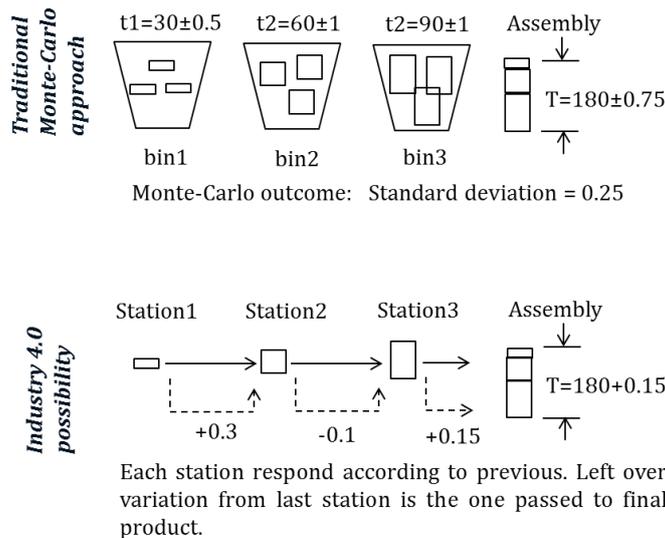


Fig. 6 A representation of traditional manufacturing and I4.0 simulations

In Figure 6, in I4.0, measurement 30.3 after the first station informs station2, aiming to make 59.7 and results in 59.6, then informs station3, aiming to make 90.1, ends up with 90.25. This results in total length T as 180.15.

Current VA tools calculate the contribution of variables to final product variation. In I4.0 it is required to find the remaining variation in the final product after all possible adjustments at each station. In I4.0 the real contributors are not the tolerances defined in the product design. Variation gets passed to the next station

- When variation status is not communicated;
- When self-adjustment is not present; and
- When self-adjustment is not enough.

Sometimes adjustability accuracy may lead to partial absorption. Measurement uncertainty also may carry over to the product, which was never a part of VA tools calculations. This means all the variation information (levels of adjustability and measurement uncertainty of each station for each DP) is required to be taken from the production concept. This may lead to the designer not to require specifying the tolerances in the drawing.

To reflect I4.0 production VA tools needs different input and output architecture. In the present VA approach, variation contribution is counted at every assembly stage and accumulated to give the final resultant variation. In I4.0 it is required to start with nominal FP and pass station by station by adding and absorbing until the end. This shifts the focus from the contribution of DP tolerances to the ability of a station to absorb variation. How much a DP is varying is not really important, so long as it may be absorbed.

3. Results

The study shows the difference required for VA tools at each stage of the present process. With I4.0, manufacturing will move forward from Zero Defect Manufacturing (ZDM) to a target of Zero Variation Manufacturing (ZVM) (Murthy *et al.* 2018). VA tools have significant scope in this change. Potential challenges identified by mapping I4.0 philosophy to the VA philosophy are:

- The aim is to calculate leftover variation, not accumulated. This changes the VA tool architecture. At every stage of assembly, some variation is generated and some absorbed. Generated is on that station equipment/machine accuracy and absorption depends on its self-adjustability. Received variation from a previous station and steps of adjustability may vary. Resultant variation of final product performance at every station is an outcome.

- DP variation should be defined as conditional instead of random. Also, the importance shifts from DPs to process stations. Performance sensitivity to DP variation is no longer so critical in I4.0. Optimization algorithms are to be focused on nullifying contribution through absorption, not reducing the contribution itself.

- Simulation of non-dimensional performances should be part of a VA tools offering. Accepting non-dimensional variables (material properties, spring constant, torque etc.) and their relationship as inputs is needed.

- The major variation in input comes from the production process concept. VA tools need to develop a manufacturing interface, into which production concept, equipment accuracies, limits and levels of adjustability can be fed. For data integrity, VA tools may exchange data with production planning tools, as they do now with CAD tools.

- Present PCDBs data need big revision, as they do not reflect I4.0 manufacturing. DP

tolerances are unknown until a new set of the database is developed. However, in this new scenario, assembly equipment accuracy may be more influential than DP tolerance. VA tools should provide options for feeding measurement uncertainty values also at each station.

- The simulation technique may need to adapt a combination of random variables and Conditionally selective variables methods, for example, Markov chain (Salimans *et al.* 2015) based, in which outcome of a stage depends on the outcome of the previous stage. Simulation reports and optimization cycles are required to align with I4.0 metrics:

Adaptability/Intelligence: Gap between absorption required and self-adjustability limitations.

IOT/CPS: Gap between measurement and communication requirements for zero variation for specific production concept.

ZVM: How many are away from the nominal performance? (Instead how many are within accepted limits?).

4. Discussion

At present, research is largely focused on changes in manufacturing processes and systems for successful I4.0 (Böckenkamp *et al.* 2017). Product design for I4.0 is yet to be strongly developed and research is required (LinkedIn. 2017). Furthermore, VA tool developers may see their tools more as production process verification tools, rather than as design verification tools. This situation, along with the challenges, many opportunities are also opened:

- Extending the present Finite Element Method (FEM) integration with VA tools, currently limited to dimensional variation, will allow performance variation (including stress development in assembly, deflections, etc.) into VA and linked to product life deterioration and service requirements.

- Categorizing variables into controlled, semi-controlled and uncontrolled parameters (Boorla and Howard 2016), simulation can identify the effect of outsourcing and optimization can recommend best production scenarios.

- Batch accuracy and measurement frequency are drivers for estimation accuracy, VA tools can recommend the operational settings for them.

- VA tools could provide different interfaces to product design and manufacturing staff to allow them to provide their inputs, and also report separately recommendations for improvement. This helps to support Ubiquitous Manufacturing (UM) concept (design anywhere and make anywhere) (Chen and Tsai 2017, Putnik 2012) developing along with I4.0.

- Performance metrics for I4.0 factories are also under development. VA tools have the opportunity to be part of the information standardization.

VA tools made compatible for I4.0 will also be suitable for simulating products made with continues process manufacturing (drugs, recipes, etc.) also (Boorla *et al.* 2017).

5. Conclusion

In conclusion, I4.0 is a game changer in manufacturing technology, and will also drastically influence VA tools. As the aim of VA tools is to replicate the production process, new trends in mass production demand them update. Study of the present VA tool architecture and work-flow along with the new I4.0 philosophy clearly shows the big changes required in accepting inputs, simulation process, target definitions and reporting system.

Along with these new challenges, VA tools have the opportunity to play a bigger role in product development in the industry than at present, by expanding variation analysis to the product lifecycle and extending outcomes to concurrent engineering and manufacturing teams.

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