

Design Synthesis Framework for Dimensional Management in Multistage Assembly System

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Abstract

This paper proposes a design synthesis framework for dimensional management in multistage assembly systems which integrate the critical design tasks: (1) Tolerance Optimization; (2) Multi-Fixture Layout Design; and, (3) Part-to-part Joint Design. The proposed framework is based on the development of: (1) a new hybrid Design Structure Matrix which integrates design tasks with design configurations of *Key Control Characteristics*, and which has the capability to model and analyze the interdependencies among design tasks and constraints; and (2) Task Flow Chain which represents the hierarchy of design tasks and is used to generate the sequence of design tasks. The proposed methodology is illustrated and validated in the process of designing configurations for automotive underbody subassembly.

Keywords:

Design synthesis, Integration, Dimensional management.

1 INTRODUCTION

Current trends in manufacturing design, specifically, time-based competition that involve frequent model changes require an enormous investment in terms of time and cost. In recent years, these challenges have been addressed through various developments in Design-for-Quality (DFQ) and Design-for-Six-Sigma (DFSS) approaches. For example, in design processes involving automotive body, shipbuilding hull, and aircraft fuselage assembly, DFQ- and DFSS-based approaches focus on dimensional variation reduction management which affects a broad range of product characteristics including production cost, downtime, product performance, functionality, and aesthetics. The impact of dimensional variation reduction management can be illustrated by the results obtained within the automotive industry in the last two decades wherein 6 sigma dimensional variation of automotive body for all *Key Product Characteristics* (KPCs) was reduced from 4-5 mm. to 2-3 mm. and further to 1.5-2.0 mm. in the most recent years [1]. These results were obtained by simultaneously reducing product development time which mainly involved eliminating a number of unnecessary engineering changes. Thus, automotive product development time was reduced from 48 months in the early 1990s to around 18 to 24 months in recent years [1]. Such reductions in dimensional variation has led to enormous cost savings in product repair and rework (\$84 US/vehicle) including additional savings related to production delays, improved production yield as well as potential market share [1].

A new product development process consists of five major stages also known as Design-Build-Test cycle which include: (1) determination of product functional requirements; (2) conceptual design; (3) detail design; (4) prototyping; and, (5) testing. Building and testing prototypes are necessary to refine engineering detail design in order to eliminate potential problems and errors related to a product before launch. However, currently there lacks a design synthesis methodology that can accurately predict variations during product/process design which are responsible for 70% of design changes in automotive and aerospace industry [2-3]. The tasks related to detail design stage involve identifying and optimizing the relationships between all KCCs which represent process variables and all KPCs. This involves adjusting design nominals which represent performance

parameters or tolerances indicated by GD&T of the selected KCCs to reduce mean shifts and variations of all the KPCs. Currently, researchers have developed numeric-based design synthesis tasks which utilize *Stream-of-Variation Methodology* (SoV/SOVA) to optimize various KCC configurations (SoV/SOVA) [4-7]. Generally, design synthesis tasks include process-oriented tolerancing, multi-fixture layout optimization, and part-to-part joint configuration, which have capability to handle a large number of KCCs (200~300 KCCs) in multistage assembly processes. While the aforementioned methods can significantly help in conducting various design synthesis tasks for dimensional management in multistage assembly system, however, there still lacks a design synthesis framework that will determine the effectiveness of each design task as well as the most effective sequence for all the design tasks.

The integration of design tasks during the development of a multistage assembly system for complex product design is necessary due to the interdependencies that exist between tasks. First, such interdependencies can potentially lead to time-consuming iterations that are needed for simulations to converge to optimal design configuration. Moreover, these interdependencies create a need for a pareto of design tasks to simultaneously satisfy dimensional management quality goal (as measure, for example, by 6 sigma) and all predetermined design constraints.

This paper addresses these challenges by proposing a design synthesis framework for dimensional management within multistage assembly systems. The methodology is based on: (1) a new hybrid Design Structure Matrix (DSM) which integrates design tasks with design configurations of KCCs which has the capability to model and analyze the interdependencies/coupling among design tasks and constraints; and, (2) Task Flow Chain (TFC) which represents the hierarchy of design tasks and is used to generate the sequence of design tasks. Designers can use these generated design task sequences as a guideline to synthesize the optimal design configurations of the system. The organization of this paper is as follows. The state-of-the-art in design synthesis is reviewed in Section 2. Sections 3 and 4 present the problem description and the methodology for the design synthesis framework, respectively. In Section 5, a case study illustrates the application of the proposed

design synthesis framework. Finally, conclusions are presented in Section 6.

2 RELATED WORK

As shown in Figure 1, currently, there are a number of methods used to enhance Design-Build-Test cycle. The Design-Build-Test cycle starts with the initial stage that defines *product functional requirement* to capture first customer needs and then translate them into the functional requirements of the product. A challenge in this stage is the difficulty to define the *KPCs* in a way that will address customer needs. Currently, functional requirements are analyzed using Quality Function Deployment (QFD) technique. The goal of the product functional requirement stage is to extrapolate set of *KPCs* that can satisfy all predefined functionality as described by customer needs. The identified set of *KPCs* is then used in subsequent design stages.

The *conceptual design stage* primarily focuses on generating *KCCs* which can satisfy all the *KPC* nominals and tolerances determined in the previous design stage. However, there are many possible sets of *KCCs* which can satisfy all the *KPC* requirements, and the criteria for selection of the optimal set of *KCCs* can vary among various methods. For example, two design methodologies widely used in this stage are: (1) Axiomatic Design (AD); and (2) Design for Manufacturing and Assembly (DFMA). Suh [8] introduced the concept of AD which provides a systematic approach to generate and refine a set of *KCCs*. AD approach is based on top-down design process wherein design solutions are generated by mapping the relationships between four design domains: Customer Attributes (CAs); Functional Requirements (FRs); Design Parameters (DPs); and, Process Variables (PVs). The design solutions are then evaluated and selected based on two design criteria defined as independence axiom and minimum information axiom. However, AD does not emphasize on designing the detail configurations of *KCCs* to control *KPC* variations within specification targets. On the other hand, DFMA-based approaches focus on minimizing assembly cost by providing heuristic guidelines that can reduce a number of potentially unnecessary *KPCs* and *KCCs*. DFMA also considers tradeoffs between additional criteria to determine the best set of *KCCs* such as manufacturability, reliability, and maintainability. DFMA is a qualitative-based design synthesis approach and relies heavily on past experience and therefore, possesses limited capability to develop new design [9].

The *detail design stage* involves adjusting the means and/or tolerances of *KCCs* to ensure that *KPCs* be at the nominals with minimum variability. The challenges in detail design stage can be classified on two levels: (1) large number of *KCCs* that needed to define design configurations; and, (2) the interdependencies between *KCCs* which not only increases the complexities involving design tasks but also creates difficulties in selecting the best sequence in which to conduct these design tasks that will address the dimensional management goals (6 sigma target). Steward [10] proposed the DSM to address these challenges by using a matrix to represent the interdependencies of design tasks as well as heuristic procedures to reduce the complexity caused by these interdependencies. In similar vein, Eppinger *et al.* [11] and Browning [12] presented the DSM hybrid model where the relations of activities and parameters are defined in the same matrix. This is a viable model as it integrates design tasks and can identify the parameters that are coupled within each task. However, the design tasks represented in the DSM approach are developed based on experience of the design team and best design practices in the past.

During the *prototyping and testing stages*, the prototypes of a product are physically built and tested in order to eliminate unforeseen errors that occur during design stages. Generally, product prototyping and testing require an enormous amount of time and can be very costly. Computer Aided Design/Manufacturing software have been introduced to mitigate some of the challenges involving time and cost expenses in an effort to visualize dimensional and geometric relations and to simulate manufacturing processes before building and testing the prototypes. Although designers can perform *what-if* scenarios in CAD/CAM environment, the adjustments of design configurations are still based on design experience. On the other hand, statistical approaches have also been introduced into the prototyping and testing stages in order to improve product design. Statistical-based design approaches, including Design-for-Six-Sigma (DFSS) and Taguchi's methods are mainly based on Design of Experiments (DOE). The DOE-based approaches focus on determining *KCCs* that have the most significant effects on the product design objectives and then formulate the analytical model to optimize their configurations. However, conducting DOE-based approaches can be very expensive and time-consuming for complex products represented by large number of

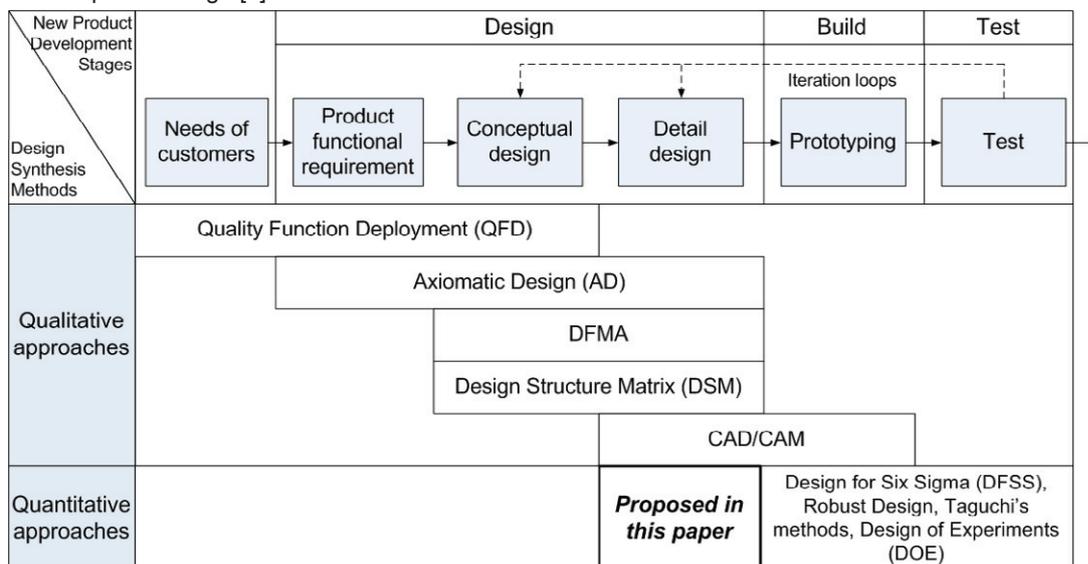


Figure 1: A short review of design methodologies used in Design-Build-Test cycle of the multistage assembly systems.

KCCs. To reduce the number of engineering changes during product launch and also to be less dependent on experience of engineers during new product development, this paper proposes a design synthesis framework to improve product dimensional quality during detail design stage by simulating and synthesizing KCC design configurations. The SOVA model is applied as an assembly response function to assess the large number of KCC design configurations synthesized by various design tasks such as process-oriented tolerance optimization, multi-fixture layout optimization, and part-to-part joint design. Then, this paper develops design synthesis framework to integrate different design tasks and select sequences of design tasks.

3 PROBLEM DESCRIPTION

The dimensional quality of a product in Six Sigma approaches is evaluated by its KPCs. The KPCs must be controlled within design specifications in order to ensure that product functions according to design intentions. In automotive body or aircraft fuselage assembly, there are numerous KCCs and KPCs with one KCC affecting many KPCs (Figure 2). In most cases a single KCC cannot function alone to satisfy KPC requirements. Additionally, the nature of relationships between KPCs and KCCs are such that product design are coupled and/or decoupled. Based on manufacturing process design, this paper groups KCCs into so-called Key Characteristic Groups (KCGs) to perform specific functions such as part-fixturing or part-joining among others in assembly process. Since KCCs within the same KCG group have similar functionality, frequently they are synthesized in a single design task such as fixture layout optimization in order to satisfy KPC required design capabilities (design nominals and minimum variation).

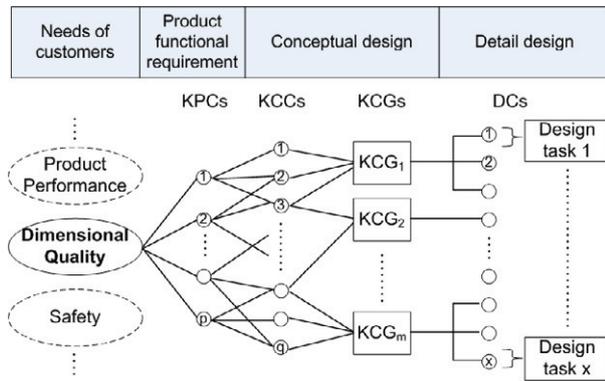


Figure 2: Mapping diagram among dimensional quality, KPCs, KCCs, KCGs, DCs, and design tasks.

An example of KPCs in the automotive door fitting process is the points used to evaluate the flushness and gap between door and side frames. Similarly, within the door fitting process, KCCs represent points used as locators in door-to-body hanging fixture or hinge-to-door assembly fixture. Hence, we group KCCs, which represent all fixture locators used during the door fitting process, into a single so-called KCG fixturing. The design configurations (DC) required for KCG fixturing are: (1) fixture planning which involves types and orientation of

locators; (2) fixture layouts consisting of locator positions; and, (3) tolerancing for all locator positions. The design task aims to synthesize each design configuration. For example, fixture layout design task is applied to determine the locator positions for all locators in a KCG fixturing group. Table 1 provides an example of the door fitting process. Figure 2 illustrates the relation between dimensional quality and design tasks.

Let us assume that KCCs in an assembly system can be grouped into m KCGs which can be expressed as:

$$\{\mathbf{KCG}_1 \ \mathbf{KCG}_2 \ \dots \ \mathbf{KCG}_m\} \quad (1)$$

Suppose that a given single \mathbf{KCG}_i ; ($i = 1, \dots, m$), has a total of n design configurations that need to be determined, as expressed in Eq. (2). Each design configuration can potentially affect all KCCs within the given \mathbf{KCG}_i .

$$\mathbf{DC}(\mathbf{KCG}_i) = \{\mathbf{DC}_1(\mathbf{KCG}_i) \ \mathbf{DC}_2(\mathbf{KCG}_i) \ \dots \ \mathbf{DC}_n(\mathbf{KCG}_i)\} \quad (2)$$

Thus, the design configurations of the assembly system can be expressed as:

$$\mathbf{DC}_{\text{system}} = \{\mathbf{DC}(\mathbf{KCG}_1) \ \mathbf{DC}(\mathbf{KCG}_2) \ \dots \ \mathbf{DC}(\mathbf{KCG}_m)\} \quad (3)$$

In this paper, design task (DT) is understood as a methodology to optimize a specific design configuration ($\mathbf{DC}_j(\mathbf{KCG}_i)$; $i \in \{1, 2, \dots, m\}$ and $j \in \{1, 2, \dots, n\}$) and is subject to a constraint function (CT). A design task usually requires a set of attribute design configurations (Φ) which are the initial design configurations that are required to start a design task. For example, a fixture layout optimization design task (DT₂) optimizes the position of each locator (DC₂) which is one of design configurations for KCG fixturing (Table 1). However, the number of locators (DC₁) and degrees of freedom that all part-to-part joints constrain (DC_{joint}) affect the optimal locator positions obtained from fixture layout design task (DT₁). Therefore, it is necessary to predetermine design configurations DC₁ and DC_{joint}, and thus both of them become a set of attribute design configurations ($\Phi_1 = \{\mathbf{DC}_1(\mathbf{KCG}_{\text{fixturing}}) \ \mathbf{DC}_{\text{joint}}(\mathbf{KCG}_{\text{joint}})\}$) of the fixture layout design task (DT₁). Each design task has a different set of attribute design configurations. The attribute design configurations can be assumed or they can be obtained from subsequently conducted design tasks.

The execution of the design task DT_k in optimizing design configuration $\mathbf{DC}_j(\mathbf{KCG}_i)$ subject to constraint function $\mathbf{CT}_k(\mathbf{DC}_{j,\text{optimal}}(\mathbf{KCG}_i))$ with a set of attribute design configurations Φ_k can be expressed as shown in Eq. (4) and can be graphically represented in Figure 3.

$$\mathbf{DT}_k(\Phi_k) : \mathbf{DC}_j(\mathbf{KCG}_i) \quad (4)$$

Subject to: $\mathbf{CT}_k(\mathbf{DC}_{j,\text{optimal}}(\mathbf{KCG}_i)) < \text{threshold}$

| KPCs | KCCs | KCG | DCs | Design Tasks |
|--|--|--------------------------|---|--|
| 1) Door Flushness 2) Door gap 3) Etc. | 1) 4-way pin 2) 2-way pin 3) NC block #1 4) NC block #2 5) NC block #3 6) Upper hinge 7) Lower hinge | KCG Fixturing | DC ₁ : Fixture Planning DC ₂ : Fixture layouts DC ₃ : Tolerances | DT ₁ : Fixture Planning Optimization DT ₂ : Fixture Layout Optimization DT ₃ : Tolerance Optimization |

Table 1: An example of mapping process for door fitting in automotive body assembly.

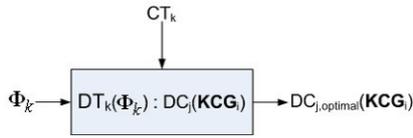


Figure 3: A single design task diagram.

The challenges of integrating different design tasks can be classified into two groups which are expressed as follows:

3.1 Coupled design tasks

The coupling between two design tasks can be basically described as a design scenario with two design tasks A and B. If task A needs a design configuration (DC) synthesized by task B, and also task B required a DC obtained from task A, the two tasks are coupled. To illustrate this, suppose that there are two design synthesis tasks (DT_1, DT_2) in synthesizing DC_1 and DC_2 which can be expressed in Eq. (5).

$$DT_1(\Phi_1) : DC_1(\bullet) \text{ and } DT_2(\Phi_2) : DC_2(\bullet) \quad (5)$$

If DT_1 and DT_2 are considered to be coupled, then $DC_1(\bullet) \subset \Phi_2$ and $DC_2(\bullet) \subset \Phi_1$. The coupled design tasks increase complexity and reduce robustness and diagnosability of the designed system.

3.2 Selection a set of design tasks

Let assume that there are n design tasks; (DT_1, \dots, DT_n), in synthesizing design configurations for improving dimensional quality. In addition, each design task is subject to a constraint function (CT_1, \dots, CT_n). It is necessary to select a minimum set of design tasks that improve dimensional quality to the predetermined level of 6 sigma variation. This can be formulated as:

$$\text{Objective: Select } \{DT\} \subset \{DT_1, \dots, DT_n\} \quad (6)$$

Subject to: (1) Quality index > 6 sigma quality threshold
(2) Minimize $\{CT\}$

To address these challenges, this paper proposes methodology to determine coupling between design tasks, and then to identify the design task sequences. The detail of the proposed methodology is presented in Section 4.

4 METHODOLOGY

This paper provides a methodology to address the challenges defined in Section 3 by first applying the hybrid DSM to reveal the coupling between design tasks and then proposing the Task Flow Chain (TFC) to generate the sets of needed design task sequences which can prevent unnecessary repetitions between design tasks. The details of each step in the proposed methodology are presented below:

Step 1: Hybrid DSM formulation

The hybrid DSM as shown in Figure 4 is used to reveal the coupling between design tasks. The columns of the hybrid DSM represent the design configurations which resulted from mapping dimensional quality, $KPCs$, $KCCs$, and $KCGs$ domains as illustrated in Figure 2. The rows of the hybrid DSM represent the design tasks in synthesizing a design configuration. The design task constraints are also incorporated into the hybrid DSM. To formulate the hybrid DSM, design configurations have to be classified into three groups corresponding to each design task. These three groups of design configurations are: (1) design configuration to be optimized shown as "O" in the DSM; (2) design configuration that is a member of a set of attribute design configurations (Φ) shown as "A" in the DSM; and, (3) design configuration which is not

considered in the design task represented by empty spaces in the matrix.

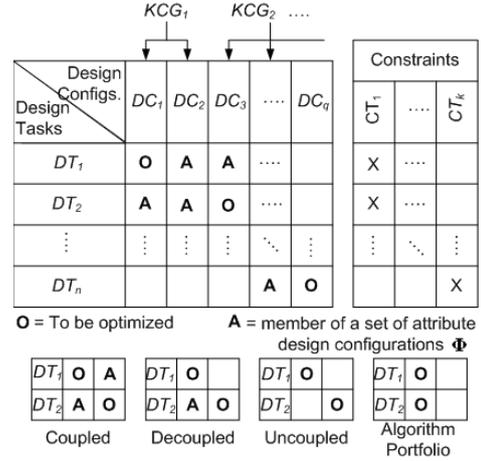


Figure 4: Hybrid Design Structure Matrix (DSM).

The hybrid DSM can explicitly reveal the coupling between design tasks. For example, configurations DC_1 and DC_3 cause the coupling between design tasks DT_1 and DT_2 as shown in Figure 4. This means that the optimized design configuration from one design task can be an input or an attribute design configuration for the other design task. To justify the sequence between these two design tasks, it is necessary to determine coupling between them as illustrated in Step 2.

Step 2: Analysis of design task coupling

In this paper, we use sensitivity analysis to determine coupling between the tasks. This allows to determine the best sequence of conducting design tasks. Sequence of two design tasks can be grouped into four scenarios:

(i) if $\partial DT_1(\Phi = DC_2) / \partial DC_2 = 0$ and $\partial DT_2(\Phi = DC_1) / \partial DC_1 = 0$, then these design tasks are *uncoupled* and can be conducted *concurrently*.

(ii) if $\partial DT_1(\Phi = DC_2) / \partial DC_2 = 0$ and $\partial DT_2(\Phi = DC_1) / \partial DC_1 \neq 0$, then these design tasks are *decoupled* and can be conducted *sequentially* ($DT_1 \rightarrow DT_2$).

(iii) if $\partial DT_1(\Phi = DC_2) / \partial DC_2 \neq 0$ and $\partial DT_2(\Phi = DC_1) / \partial DC_1 \neq 0$, then these design tasks are *coupled* and can be conducted *sequentially* with additional *iteration loops*. In this case the process of conducting these design tasks sequentially may not lead to the best design configurations; however it can be justified as tradeoff between reaching the optimal solution and computation time efforts. The initial sequence between two tasks DT_1 and DT_2 can be determined using sensitivity analysis.

$$\text{If } \frac{\partial DT_1(\Phi = DC_2)}{\partial DC_2} > \frac{\partial DT_2(\Phi = DC_1)}{\partial DC_1}, \text{ then } DT_2 \rightarrow DT_1 \quad (7)$$

Equation (7) can be interpreted as the optimal design configuration DC_2 obtained from DT_2 is less sensitive to the changes of its attribute design configuration (Φ) than optimal design configuration DC_1 obtained from DT_1 . Therefore, DT_2 does not depend on information included in DC_1 , and thus all initial conditions for DC_1 can be arbitrary set in conducting design task DT_2 .

(iv) If $\partial DT_1(\Phi = DC_2) / \partial DC_2 = 1$ and $\partial DT_2(\Phi = DC_1) / \partial DC_1 = 1$, then these two design tasks optimize the same design configuration using two different algorithms and can be conducted *concurrently* which the better solution is selected using performance measure. This scenario can be described as *algorithm portfolio*.

Step 3: Task flow chain (TFC) development

The TFC is developed to generate sequences of design tasks. The most independent design task is placed on the upper left position and all other design tasks which are less independent are placed in cascading mode to the most dependent design task at the lower right of the diagram as shown in Figure 5. The optimal design configurations from design tasks at higher level of independency can be used as an attribute design configuration in the lower level design tasks. The sequences of design tasks can be generated by combination of design tasks in TFC.

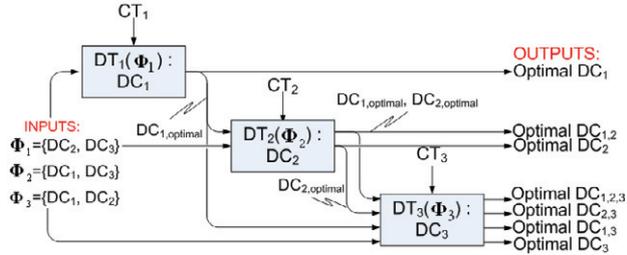


Figure 5: Task Flow Chain (TFC) diagram.

Step 4: Evaluate and select design task sequence

The generated design task sequences from Step 3 are evaluated in terms of their dimensional quality and constraints. At this stage, numerical simulation techniques such as Monte Carlo simulations can be used to assess design dimensional quality [3]. Those design task sequences that meet the quality and constraint threshold can then be selected and are benchmarked for the purposes of best design task sequence option.

5 CASE STUDY

The Floor Pan is one of the subassemblies in the automotive underbody which consists of four parts: Floor Pan Left and Right, and Bracket Left and Right, assembled in three stations as shown in Figure 6.

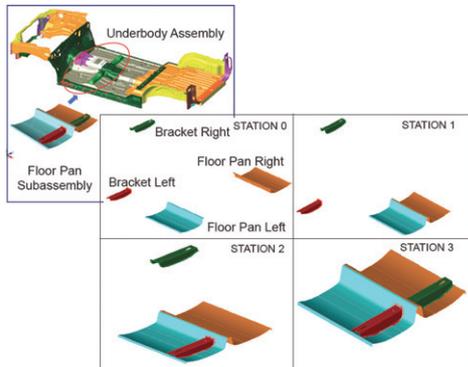


Figure 6: Automotive underbody assembly.

Dimensional quality of Floor Pan Assembly is characterized by 12 KPCs which depends on the variations of 63 critical KCCs. These 63 KCCs can be grouped into two Key Control Groups (KCGs); (1) mating joint group (KCG₁); and (2) fixturing group (KCG₂). The mating joint group (KCG₁) is required to define three design configurations which are: (1) the direction of DOFs constrained by a mating joint (DC₁); (2) a number of DOFs constrained by a mating joint (DC₂), and (3) tolerances of a mating joint (DC₄). The fixturing (KCG₂) is also required to define three design configurations which are: (1) a number of DOFs constrained by fixture layout (DC₂); (2) the locator positions (DC₃); and (3) position tolerances of locators in each fixtures (DC₄).

Generally, three design tasks (DTs) are conducted to optimize these design configurations. First, mating joint design task (DT₁) is conducted to determine the direction

that a mating joint should constrain the mating part (DC₁) in order to minimize variation propagation. The assembly tool accessibility (CT₁) is the constraint corresponding to this design task. Multi-Fixture Layout design task (DT₂) is conducted to determine a set of fixture layouts (DC₃) in three assembly stations which are not sensitive to the variations of all 63 KCCs. The constraint related to fixture layout design is the stability of parts during part positioning process (CT₂). Last, tolerance optimization (DT₃) is used to assess the optimal tolerances (DC₄) of all KCCs where fabrication and assembly cost (CT₃) is selected as a constraint. The proposed methodology applied to the Floor Pan Assembly is as follows:

Step 1: Hybrid DSM formulation

Three design tasks, four design configurations, and three constraints are mapped in the hybrid DSM as shown in Figure 7. The hybrid DSM shows that there are coupling between the mating joint design (DT₁) and multi-fixture layout design (DT₂) since the optimal fixture location can be an attribute design configuration for DT₁ and constraint direction of mating joint (DC₁) can be an attribute design configuration for DT₂. Tolerance Optimization (DT₃) is decoupled from those two design tasks.

| Design Config. | Design Configurations | | | | Constraints | | |
|--|--|---|---|-------------------------------|--|---------------------------------------|--------------------------------------|
| | Constrained direction of DOFs (DC ₁) | Number of DOFs constrained (DC ₂) | Locations of fixture (DC ₃) | Tolerances (DC ₄) | Assembly Tool Accessibility (CT ₁) | Assembly stability (CT ₂) | Cost of Tolerance (CT ₃) |
| Design Tasks | | | | | | | |
| Mating Joint Design (DT ₁) | o | A | A | | X | | |
| Multi-Fixture Layout Design (DT ₂) | A | A | o | | | X | |
| Tolerance Optimization (DT ₃) | A | A | A | o | | | X |

o = To be optimized A = member of a set of attribute design configurations X = Constraint of DT

Figure 7: Hybrid DSM for Floor Pan Subassembly.

Step 2: Analysis of design task coupling

This paper applies sensitivity analysis to the case study in order to decouple mating joint design task (DT₁) and multi-fixture layout design task (DT₂). The sensitivity of mating joint design task (DT₁) against locations of fixtures (DC₃) is shown in Figure 8. The sensitivity, $\partial DT_1 / \partial DC_3$, is equal to zero since the optimal constraint directions of the mating joint (DC₁) are at 90 degree of mating angle in two different fixture layout design. Thus, we can conclude that the mating joint design task, DT₁, can be decoupled from multi-fixture layout design task, DT₂.

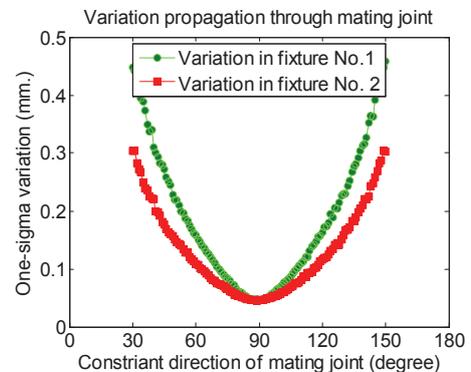


Figure 8: Variation of measurement point at different mating joint design.

Step 3: Task flow chain development

Since mating joint design task (DT₁) can be decoupled from multi-fixture layout design task (DT₂), the design task DT₁ can be performed independently without

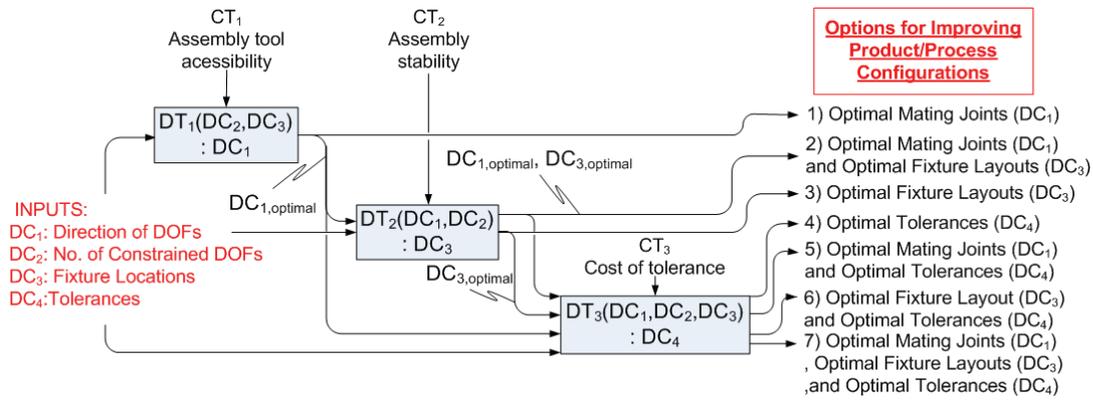


Figure 9: Task Flow Chain for Floor Pan Assembly.

requiring any feedback from fixture layout design task (DT₂). Thus, the task flow chain can be developed as shown in Figure 9. Seven sequences of design tasks can be generated from the task flow chain. The design task sequence options (3), (4), and (6) are evaluated and benchmark for their performance.

Step 4: Evaluate and select design task sequence

Dimensional quality and cost of tolerances (CT₃) are used for benchmarking the design task sequences Option 3 (Multi-Fixture Layout design task), Option 4 (tolerance optimization design task), and Option 6 (Integration of Multi-Fixture Layout and Tolerance Optimization design tasks). The Process Capability Index (C_p) is used to assess the variations of all 12 KPCs:

$$C_p = (USL - LSL) / \sigma \quad (8)$$

where USL and LSL are the given upper and lower specification limits of a measurement point, respectively and σ is the standard deviation of each KPC obtained from Monte Carlo simulation. The average improvement of C_p for 12 KPCs and cost of tolerances in each design tasks sequence option are shown in Table 2.

| Design Task Sequence Options | Tolerance Cost Increase | Average C _p Improvement |
|--|-------------------------|------------------------------------|
| Option (3): DT ₂ | 0% | 30.88% |
| Option (4): DT ₁ | 9.05% | 55.43% |
| Option(6): Integration of DT ₂ and DT ₁ | 3.98% | 76.36% |

Table 2: Process Capability improvement and cost of tolerances from design Options (3), (4), and (6).

The design task for sequence Option 6 which is the integration of multi-fixture layout design (DT₂) with tolerance optimization (DT₃) provides the highest C_p improvement at the minimum increase tolerance cost.

6 CONCLUSIONS

This paper developed a design synthesis framework for a dimensional management in multistage assembly systems. The methodology takes into consideration interdependencies between design synthesis tasks to determine a Pareto and optimal sequences of design tasks to satisfy dimensional management quality goal and all predetermined design constraints. The application of the proposed methodology is illustrated through a case study using an automotive underbody assembly which integrates three design synthesis tasks, namely: (1) Process-oriented tolerance optimization; (2) Multi-fixture layout optimization; and, (3) Part-to-part joint design. The results from the case study show that the proposed framework can help in generating design tasks sequences which can minimize simulation time as well as benchmark

design task sequences in terms of dimensional quality improvement and considering constraints.

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