Quality-driven Sequence Planning and Line Configuration Selection for Compliant Structure Assemblies

H. Wang, D. Ceglarek (2)
Department of Industrial and System Engineering
The University of Wisconsin-Madison
1513 University Avenue, Madison, WI 53706-1572, USA

Abstract

Assembly sequence planning is an integral part of a new product and process development. However, currently there are very few available approaches to evaluate the impact of assembly sequences on product quality. This paper develops a methodology for Quality-driven Sequence Planning (Q/SP) with consideration to product dimensional quality based on the following three steps: (1) Sequence generation for predetermined line configurations using *k*-piece mixed-graph representation of assembly; (2) Dimensional quality model of variation propagation for assembly processes with compliant parts; and (3) Evaluation of sequences based on the multivariate process capability index. The methodology is illustrated using an industrial case study.

Keywords:
Assembly Sequencing , Dimensional Quality, Line Configuration Selection

1 INTRODUCTION

1.1 Motivation

Assembly sequence planning plays a pivotal role in many production engineering activities such as line configuration and tooling development. Much of previous research has investigated assembly sequence planning under the assumption that parts are manufactured accurately at their nominal dimensions. However, manufacturing processes are inherently imprecise. It has been reported that 67-70% of all design changes in the aerospace and automotive assembly processes are related to product-dimensional variations [1] [2]. Managing variations is essential to retaining competitiveness since excessive variations can directly affect productivity, and ultimately, product quality. Different sequences will establish different ways of variation propagation and hence, result in different variations on the final product. There is an important recent effort, albeit preliminary, that attempts assembly sequencing feasibility analysis with toleranced parts [3]. However, like most previous research in sequence planning it was conducted during detail assembly planning phase of a new product development process. Potentially, more gains can be achieved if assembly sequence planning method is applied at the earliest possible assembly planning phase. Such early application of assembly planning, particularly with consideration to variation management will decrease the need for costly and time consuming revisions at later product development phases.

In order to evaluate assembly sequences with criteria of dimensional quality, it is imperative to have an appropriate quality model on variation propagation for multi-station assemblies. For sheet metal assemblies which are widely used in automotive, aerospace, and household appliance industries, part flexibility interacts with part fabrication errors, tooling errors, and part-to-part joint geometry in a multi-station setting. Shiu et al. [4] developed a beam-based product and process model for variation propagation analysis at early design phase. However, their model was developed for a single station process.

Furthermore, to date no method exists to generate sequences for any predetermined line configuration(s), i.e., for any *k*-ary assembly processes where *k* or less parts or subassemblies are assembled at each station in a given multi-station line configuration. Existing methods in sequence generation operated under the assumption of a binary assembly process where exactly two parts or subassemblies are assembled at each station in a multi-station line configuration.

The objective of this paper is to develop a methodology for Quality-driven Sequence Planning (Q/SP) with consideration of assembly line configuration and product dimensional quality. The developed Q/SP methodology allows one to obtain a robust assembly system which is less sensitive to part and tool variations by selection of assembly line configurations and sequences at early product development phases (Table 1).

1.2 Proposed methodology

This paper addresses the aforementioned problems by developing the Q/PS methodology for sequence planning which: (i) considers product quality, (ii) can be applied at early product development phase; and (iii) allows to generate sequences for any line configuration with a generic *k*-ary assembly processes.

The Q/PS methodology considers selection of assembly line configuration to obtain a set of robust assembly systems which are less sensitive to part and tool variations. The presented Q/PS methodology is based on three steps:

(1) Sequence generation approach for all possible line configurations (Section 2.1). This approach is based on a new method of sequence generations with any predetermined assembly line configuration. Here, the *k*-piece mixed-graph is utilized to locate all feasible subassemblies at each station. This expands the current approaches applicable only for binary assembly processes (wherein two parts or subassemblies are joined at any station) to *k*-ary assembly processes (where *k* parts or subassemblies are joined at any station, and *k* can be any integer).

(2) Dimensional quality represented as product variation propagation is modeled using beam-based model (Section 2.2). The development of beam-based multi-station model offers an opportunity to advance sequence planning at early phases of assembly planning. The developed beam-based model allows the advantage of modeling variation propagation in multi-station assembly processes in which part flexibility interacts with part fabrication errors, tooling errors, and part-to-part joint geometry. In addition, it makes the modeling procedure computationally efficient which makes it applicable in sequence planning. The model integrates available product and process information based on extracted common attributes, key product characteristics and key control characteristics.

(3) Evaluation of assembly sequences and line configurations using the multivariate process capability index MC_{pm}. The Q/PS methodology allows the evaluation of assembly sequences which further leads to the evaluation of assembly line configurations using product dimensional quality as criteria. Here assembly sequence evaluation is represented as a discrete optimization problem. An evaluation index, $\hat{O}_j$, is developed to achieve the best sequence(s) for a given fixture locating schemes.

Process design phase / Sequence evaluation criteria	**Early assembly planning**	**Detail assembly planning**
Currently used criteria (Assume that parts and tooling are at their nominal dimensions)	*Hard constraints*: Part and tool accessibility, part stability ([5] [6], etc.) *Goodness measure indices*: DFA-based measures such as min. number of re-fixturing and re-orientation, max. parallelism. ([7] [8], etc.)	*Hard constraints*: Part and tool accessibility, part stability ([9] [10], etc.) *Goodness measure indices*: Min. overall cost, line balancing, min. fixture complexity, max. part stability, and other DFA-based measures such as ease of assembly, grouping of similar tasks, etc. ([10] [11] [12], etc.)
Dimensional Quality (Consider that parts and tooling have dimensional variations)	*Hard constraints*: No published research *Goodness measure indices*: Max. quality ([**To be presented in this paper**])	*Hard constraints*: Part-to-part interference ([3]). *Goodness measure indices*: No published research

Table 1: Position of the presented research in the literature of assembly sequence planning.

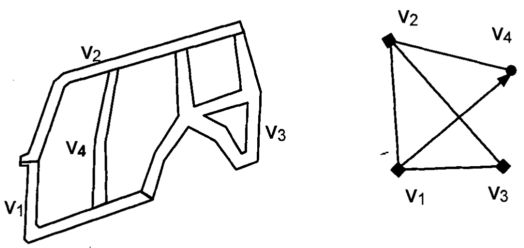
2 QUALITY-DRIVEN ASSEMBLY SEQUENCE PLANNING

2.1 Sequence generation for assembly line configuration

In this section, a new method is presented to generate all possible sequences with any predetermined assembly line configuration. The method of *k*-piece mixed-graph is utilized to locate all feasible subassemblies at each station. The sequence generation method is based on four iterative steps:

Step I: At station *i*, develop Datum Flow Chain (DFC), M^i, for the assembly, where a vertex represents a discrete assembly component (part or subassembly) and an edge represents relationship between two components if they have [13]. A directed edge represents the locating relationship between two components. The DFC graph of side aperture of a Sports Utility Vehicle (SUV) is shown in Figure 1.

v_1 - Panel rocker	v_3 - Rear quarter panel
v_2 - A-pillar + roof side	v_4 - B-pillar



(a) Side aperture assembly (b) The DFC representation

Figure 1: Side aperture assembly.

Step II: Develop *k*-piece mixed-graph, $C^{k_i}(M^i)$ representation of the assembly at station *i*, where a source vertex represents a possible *k*-ary subassembly. The *k*-piece mixed-graph is generated from the DFC, M^i, as follows: vertex set consists of all induced connected *k*-vertex subgraphs of M^i; two vertices of $C^{k_i}(M^i)$ are adjacent in $C^{k_i}(M^i)$ if subgraph intersection is a connected (*k*-1)-vertex subgraph.

The *k*-piece mixed-graph generalizes the DFC representation to include all possible *k*-ary assemblies. Figure 2 shows an example of *k*-piece mixed-graph for the side aperture assembly.

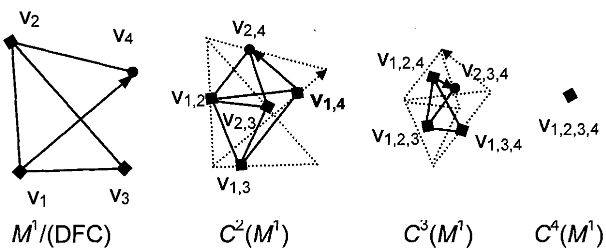


Figure 2: Illustration of generating k-piece mixed-graph from the DFC of the side aperture

Step III: Select a feasible subassembly by selecting a vertex in $C^{k_i}(M^i)$ for a given k_i, e.g., vertex $v_{1,4}$ in Figure 3. All vertices for a given k_i represent all possible sequences of k-ary assemblies at station *i*. For example, (v_1v_4), (v_1v_2), (v_1v_3), and (v_2v_3) for k_1=2 shown in Figure 3.

Step IV: Repeat steps I, II, and III for station (*i*+1).

The above four steps are used iteratively to generate all sequences at each station.

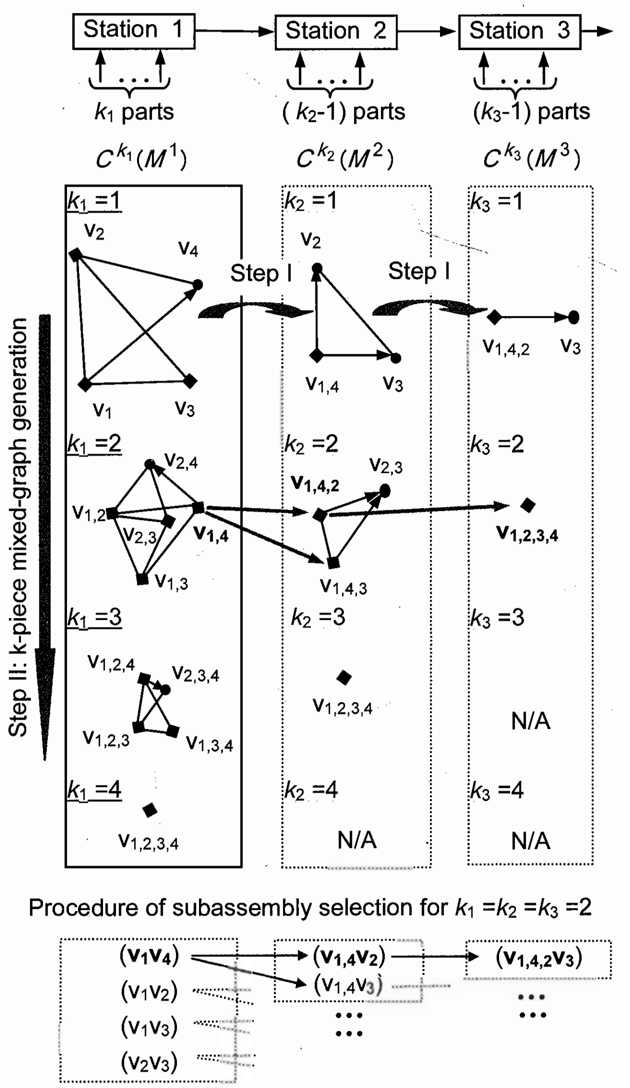


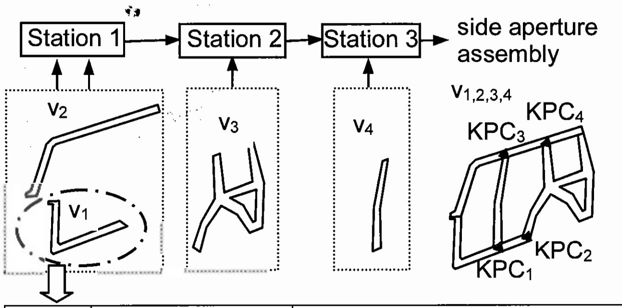
Figure 3: Illustration of subassembly selection for a multi-station setting based on the method of *k*-piece mixed-graph.

2.2 Beam-based quality model for variation propagation

Evaluation of assembly sequence with criteria for dimensional quality requires an appropriate quality model on variation propagation. Product quality is characterized by a group of features that could greatly affect the designed functionality and the level of customer satisfaction. In automotive or aerospace industries, these critical features are known as KPCs (Key Product Characteristics). The fixture locator layout and part-to-part joints, the determining factors in achieving the required dimensional accuracy of the KPCs, are known as KCCs (Key Control Characteristics).

As case in point, a beam-based modeling of variation propagation is presented for multi-station compliant structure assembly processes which can be used at an early design phase for the automotive body assembly. A generic description of the automotive body assembly process was presented in [14] [15]. The beam-based model of the assembly is represented in Equation (1) and illustrated in Figure 4 using the example of the automotive side aperture assembly. Each part v_j is represented as beams with defined material (Young's modulus, E) and geometry (moment of inertia I_y and I_z, cross section A, starting node P_0 and ending node P_1). Additionally, each part is associated with KPCs used for part/product dimensional evaluation and KCCs which represents fixture locators called Principal Locating Points (PLPs) and part-to-part joints called Joint Location Points (JLPs). Each PLP is mathematically modeled by Cartesian coordinates (x,y,z) and direction of constraint (**d**). Each JLP, which consists two points and vectors, is mathematically modeled by Cartesian coordinates (x,y,z), direction of joining operation (**p**) and kinematic characteristic of joining operation (e).

$$\begin{cases} \text{Parts: } \{v_1, v_2, \ldots, v_m\} \\ v_j = \{\{\text{Beam}\}_{vj}, \{\text{KPC}\}_{vj}, \{\text{KCC}\}_{vj}\} \\ \text{Beam} = \{E, I_y, I_z, A, P_0, P_1\} \\ \text{KPC} = \{\text{Measurement point}\} = \{(x, y, z)\} \\ \text{KCC} = \{\{\text{PLP}\}, \{\text{JLP}\}\} \\ \text{PLP} = \{(x, y, z), \mathbf{d}\} \\ \text{JLP} = \{(x, y, z), \mathbf{p}, e\} \end{cases} \quad (1)$$



KCs	Illustration	Mathematical model
KPC	KPC_2 KPC_1	(x,y,z)
KCC	Principal Locating Point (Locator) PLP_1 PLP_3 PLP_2	d_1 (x,y,z)
	Joint Location Point JLP_1 JLP_3 JLP_2	e=1: self-equalized joining (x_1,y_1,z_1) p_2 v_3 p_1 (x_2,y_2,z_2) v_1 e=2: position-controlled joining (x_1,y_1,z_1) v_3 p_1 (x_2,y_2,z_2) v_1 e=3: seam-filled joining (x_1,y_1,z_1) v_3 (x_2,y_2,z_2) v_1

Figure 4: Illustration of modeling of the side aperture assembly.

Tolerance analysis is conducted with the assumption that deviations at the KCC points are normally distributed and all tolerance limits correspond to their 6σ values. A number theory-based technique (NT-net) [16] is used to obtain the estimated process mean shifts, $\Delta\bar{X}$, and the estimated covariance matrix, $\hat{\Sigma}$, of the KPCs. The functional relationship between KPCs and KCCs used in simulations is shown in Equation (2).

$$\left(\hat{\Sigma}, \Delta\bar{X}\right) = f\left(\Lambda_{KCC}, \Delta\bar{X}_{KCC}\right) \quad (2)$$

where, Λ_{KCC} is the input variance matrix of the independent KCCs, and $\Delta\bar{X}_{KCC}$ is the vector of mean shifts of the KCCs.

2.3 Quality-driven evaluation of assembly sequences and line configurations

A robust assembly system which is less sensitive to input variations can be obtained at early phases of a new product development through the selection of assembly line configurations and sequences.

The final evaluation of the assembly can be done by evaluating means and variances of the KPCs for given input variations of the KCCs. Different assembly sequences and line configurations affect the relations between KCCs and KPCs in terms of variations and mean shifts. The functional relationship between KPCs and KCCs for a given sequence *j* is represented in Equation (3).

$$\left(\hat{\Sigma}_j, \Delta\bar{X}_j\right) = f\left(\Lambda_{KCC}, \Delta\bar{X}_{KCC}, j\right) \quad (3)$$

where, $\Delta\bar{X}_j$ and $\hat{\Sigma}_j$ are the estimated vector of process mean shift and covariance matrix of the KPCs for process sequence *j*, respectively.

Evaluation index

A multivariate capability index MC_{pm}, which considers asymmetric tolerances, is selected in this paper to evaluate assembly sequences [17].

$$MC_{pm,j} = \hat{C}_{p,j} / \hat{D}_j \quad (4)$$

where $\hat{C}_{p,j} = \dfrac{\text{[Volume of Specified Tolerance Region]}}{\left|\hat{\Sigma}_j\right|^{1/2} (\pi L)^{v/2} \left[\Gamma(v/2+1)\right]^{-1}}$,

$$\hat{D}_j = \left[1 + \frac{n}{n-1} \Delta\bar{X}_j{}' \hat{\Sigma}_j^{-1} \Delta\bar{X}_j\right]^{1/2}$$

where, L is the 99.73% quantile of a χ^2 distribution; |.| denotes the determinant; v is the total number of KPCs; $\Gamma(\alpha)$ is the gamma function defined as $\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy$; n is the number of sample simulation runs for sequence *j*, and $n\ /\ (n-1) \approx 1$ with a large number of simulation runs The numerator $\hat{C}_{p,j}$ is a ratio of allowable process dispersion and simulated process dispersion calculated for sequence *j*. That is, a value of $\hat{C}_{p,j}$ greater than 1 implies that the process has smaller variation than allowed by the specification limits within a certain confidence level. 0 $1/\hat{D}_j$ <1 measures the closeness between the process mean and the target; a larger $1/\hat{D}_j$ indicates that the mean vector is closer to the target mean vector.

In this paper, the assembly sequences are evaluated by mean shifts $\Delta\bar{X}_j$ and variations $\hat{\Sigma}_j$ of KPCs. Then , the final evaluation index can be represented as:

$$\hat{O}_j = \left[\hat{\Sigma}_j\left(1 + \Delta\bar{X}_j{}' \hat{\Sigma}_j^{-1} \Delta\bar{X}_j\right)\right]^{-1/2} \quad (5)$$

where $\hat{O}_j$ is the evaluation measure for sequence *j*.

Methodology of the quality-driven evaluation

The procedure of the Q/SP methodology for quality-driven line configuration and sequence evaluation is shown in Figure 5.

All line configurations $\{k_1, k_2, \ldots, k_{Ns}\}$ are presented for given number of parts N_p, maximum allowed number of station N_s, and maximum k_i-ary assembly at each station *i*.

All sequences J for all the line configurations are generated using the *k*-piece mixed-graph method presented in Section 2.1. Quality-driven evaluation of the sequences for all line configurations is conducted by running beam-based variation model and calculating evaluation index $\hat{O}_j$ for each sequence (Equation (5)). The best sequence(s) are found by Max($\hat{O}_j$). The procedure is implemented in FEM simulation software.

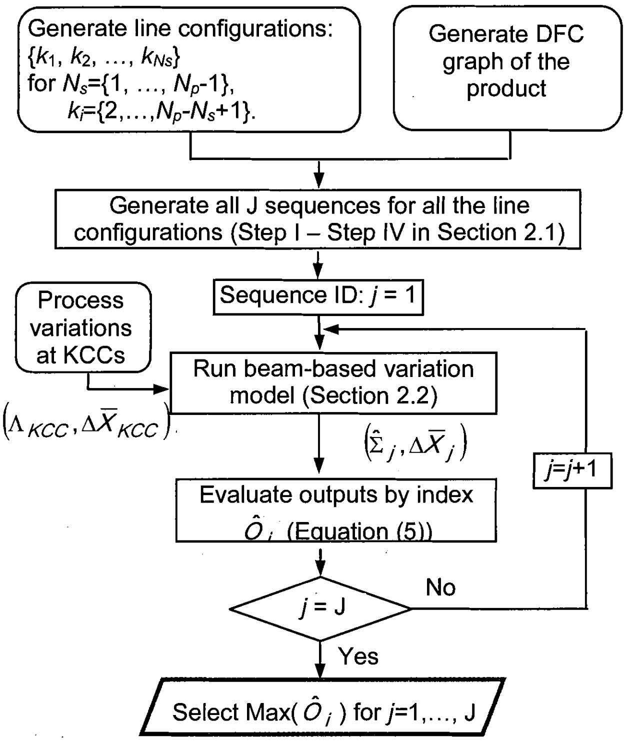


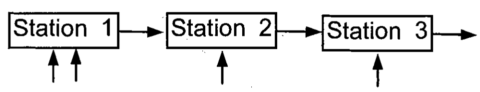
Figure 5: The procedure of the quality-driven assembly sequence planning.

3 INDUSTRIAL CASE STUDY

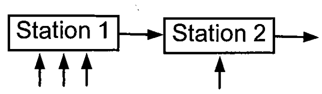
The assembly process of the SUV side aperture, discussed in Section 2, is used to illustrate the sequence and line configuration evaluation results. All PLP input tolerances are ±1.0 mm. Part fabrication tolerances are ±2.0 mm at part-to-part joints. It is assumed that deviations at the KCC points are normally distributed and all tolerance limits correspond to their 6σ values. NT-net simulations are used for each sequence, and the covariance matrix and mean shift vector of the four KPCs are obtained.

With number of parts N_p = 4, three line configurations shown below are evaluated and the results of their evaluation is shown in Figure 6.

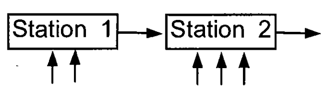
Line 1: (Ns = 3, $k_1 = k_2 = k_3 = 2$)



Line 2: (Ns = 2, k_1 = 3, k_2 = 2)



Line 3: (Ns = 2, k_1 = 2, k_2 = 3)



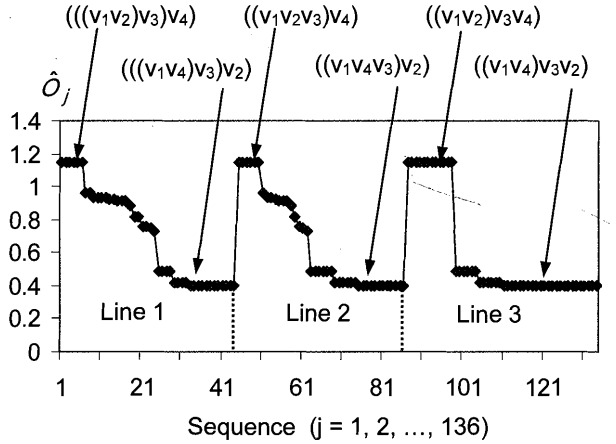


Figure 6: Evaluation index values of the sequences for the example of side aperture assembly.

The results show that assembly sequences as well as line configurations affect significantly product dimensional quality. Additionally, for each line configuration there exist sequences which produce the best product quality. As Figure 6 shows, the maximum value of $\hat{O}_j$ (=1.1453) happens at certain sequences of all the three line configurations: (i) the sequence (((v_1 v_2) v_3) v_4) of line 1, (ii) the sequence ((v_1 v_2 v_3) v_4) of line 2, and (iii) the sequence ((v_1 v_2) v_3 v_4) of line 3. Therefore, the Q/SP method can be used in early design phases for line configuration and sequence planning to improve product quality.

4 SUMMARY

This paper develops a methodology for quality-driven sequence planning (Q/SP) which: (i) considers product quality, (ii) can be applied at early product development phase; and (iii) allows to generate sequences for any line configuration with a generic *k*-ary assembly process.

The Q/PS methodology considers selection of assembly line configurations to obtain a set of robust assembly systems which are less sensitive to part and tool variations. The presented Q/PS methodology is based on three steps: (1) sequence generation approach for all possible line configurations/layouts; (2) dimensional quality represented as product variation propagation modeled using beam-based model; and (3) evaluation of assembly sequences and line configurations using the multivariate process capability index.

The conducted simulations of one industrial case study allowed to select three best assembly line configurations and sequences.

5 REFERENCES

[1] Shalon, D., Gossard, D., Ulrich, K., and Fitzpatrick, D., 1992, Representing Geometric Variations in Complex Structural Assemblies on CAD Systems, Proceedings of the 19th Annual ASME Advances in Design Automation Conference, Vol. DE-44, No. 2: 121-132.

[2] Ceglarek, D. and Shi, J., 1995, Dimensional Variation Reduction for Automotive Body Assembly Manufacturing, Manufacturing Review, Vol. 8, No. 2: 139-154.

[3] Latombe J.C., Wilson R.H., Cazals F., 1997, Assembly Sequencing with Toleranced Parts, Computer-aided Design, Vol. 29, No. 2:159-174.

[4] Shiu, B.W., Apley, D., and Ceglarek, D., 2003, Tolerance Allocation for Sheet Metal Assembly using Beam-Based Model, Trans. of IIE, Design and Manufacturing, Vol. 35, No. 4: 329-342.

[5] Srinivasan H., Gadh R., 2001, A Non-interfering Selective Disassembly Sequence for Components with Geometric Constraints, IIE Transactions, Vol. 34, No. 4: 349-361.

[6] Dini, G., Santochi, M., 1992, Automated Sequencing and Subassembly Detection in Assembly Planning, Annals of the CIRP, 41/1:1-4.

[7] Homem de Mello, L.S., Sanderson, A.C., 1991, 2 Criteria for the Selection of Assembly Plans – Maximizing the Flexibility of Sequencing the Assembly Tasks and Minimizing the Assembly Time through Parallel Execution of Assembly Tasks, IEEE Transactions on Robotics and Automation, Vol. 7, No. 5: 626-633.

[8] De Fazio, T.L., Rhee S.J., Whitney D.E., 1999, Design-specific Approach to Design for Assembly (DFA) for Complex Mechanical Assemblies, IEEE Transactions on Robotics and Automation, Vol. 15, No. 5: 869-881.

[9] Baldwin, D.F., Abell T.E., Lui M-C, De Fazio T.L., Whitney D.E., 1991, An Integrated Computer Aid for Generating and Evaluating Assembly Sequences for Mechanical Products, IEEE Transactions on Robotics and Automation, Vol. 7, No. 1: 78-94

[10] Laperriere L., ElMaraghy H.A., 1996, GAPP: A generative assembly process planner, Journal of Manufacturing System, Vol. 15, No. 4: 282-293.

[11] Dini, G., Failli, F., Lazzerini, B., Marcelloni, F., 1999, Generation of Optimized Assembly Sequences Using Genetic Algorithms, Annals of the CIRP, 48/1:17-20.

[12] Laperrrière, D., ElMaraghy H.A., 1992, Planning of Products Assembly and Disassembly, Annals of the CIRP, 41/1:5-9.

[13] Mantripragada R., and Whitney D.E., 1998, The datum flow chain: A systematic approach to assembly design and modeling, Research in Engineering Design, Vol. 10: 150–165.

[14] Ceglarek, D., Shi, J., and Wu, S.M., 1994, A Knowledge-based Diagnosis Approach for the Launch of the Auto-body Assembly Process, Trans. of ASME, Journal of Engineering for Industry, Vol. 116, No. 4: 491-499.

[15] Camelio, J., Hu, S.J., and Ceglarek, D., 2003, Modeling Variation Propagation of Multi-station Assembly Systems with Compliant Parts, Trans. of ASME, Journal of Mechanical Design, Vol. 125, No. 4: 673-681.

[16] Huang, W., Ceglarek, D., 2004, Tolerance Analysis for Design of Multistage Manufacturing Processes using Number-Theoretical Net Method (NT-net), International Journal of Flexible Manufacturing Systems, Vol. 16, No.1: 65-90.

[17] Taam, W., Subbaiah, P., and Liddy, J.W., 1993, A Note on Multivariate Capability Indices, Journal of Applied Statistics, Vol. 20, No. 3: 339-351.