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Manufacturing Process Planning in Set-Based Concurrent Engineering Paradigm

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Abstract. The integration of manufacturing planning activities into early design decisions is paramount. Manufacturing constraints and opportunities should be investigated early in a product development (PD) stages to launch products successfully. Set-based concurrent engineering (SBCE) paradigm is pronounced in literature and believed to form the foundation of lean thinking in PD. In SBCE, alternative product-subsystems are explored simultaneously and weak design choices are progressively eliminated as more knowledge about manufacturability becomes known. However, there is a methodological gap on how to execute SBCE in practice and integrate manufacturing process planning.

This paper aims at conceptualizing the requirements to start manufacturing planning in the realm of SBCE paradigm. At the same time, the paper proposes a dialogue mechanism through which designers and manufacturing process planners are able to explore and evaluate alternative conceptual designs and process plans in parallel. Moreover, the methodology enables design and process knowledge to be effectively integrated for a better decision making.

Keywords. Product Development (PD), Set-Based Concurrent Engineering (SBCE), Manufacturing Process Planning.

1 Introduction to Set-based Concurrent Engineering (SBCE)

The traditional approach to develop a product concept, shown in the left part of Figure 1, typically starts with breaking the product down into subsystem, defining detailed requirements for each module and deriving a small number of alternative solutions which are suited to meet the initial requirements. Engineers then quickly assess the solutions and select the most promising one to be pursued in the further PD process. For the selected solution they develop drafts, build prototypes and conduct tests to more and more specify the particular alternative. This process, however, rarely turns out to be linear in nature. Usually, when specifying the module, engineers discover that the particular specification chosen does not meet the requirements formulated at the beginning because of manufacturability and other uncertainties. They then go through iterative loops to either modify the concept until it satisfies their particular need or start the process over by selecting a completely different alternative. Because of its iterative nature where engineers move from point to point in the realm of possible designs, this paradigm has been termed point-based concurrent engineering (PBCE) [1] and [2].

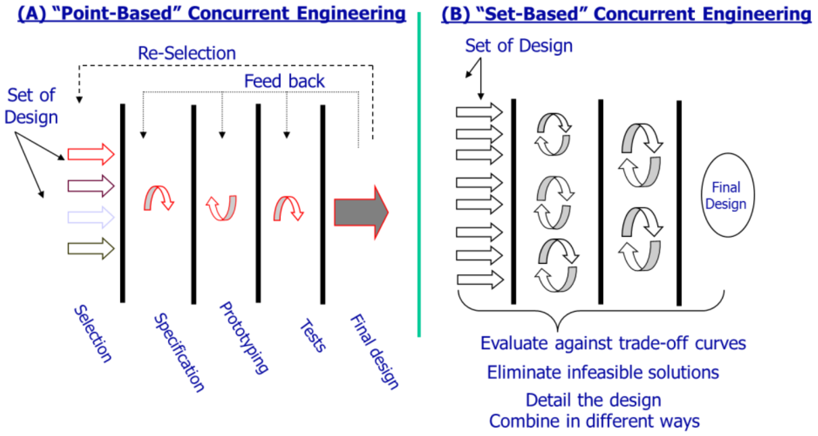


Fig. 1. Comparison between Point and Set-Based Concurrent Engineering

An alternative to the PBCE is set-based concurrent engineering (SBCE), the general systematic of which is depicted in the right part of Figure 1. SBCE was first used by Toyota [1]. Like PBCE, SBCE starts with dividing the product into small subsystems and modules. However, unlike in PBCE, no detailed requirements are defined for these subsystems. Instead, engineers only identify broad targets for every module. Based on these general objectives, a much larger number of alternative solutions for every component are developed early in the process. Designers design, test and analyze multiple solutions for every subsystem in parallel [3]. Unless designers have sufficient knowledge to eliminate an alternative, it will be kept for further investigation.

SBCE is more advantageous compared to PBCE. First, it is a known fact that design reworks increase as a project approaches production launch, once resources have already been committed. Therefore, front-loading the PD process by exploring alternatives early in the process instead of iterating in later stages is likely to reduce the overall cost of PD [4]. Second, late engineering changes cause disruption in the overall schedule of the project, and cause unpredictability in the downstream activities [5]. SBCE's principle of delaying decision makes sense for designers to avoid disruptions of process flow. Third, quality and innovation level improved by adopting SBCE. Exploring alternative design solutions and studying the feasibilities using proven data and knowledge at early stages support engineers to find more innovative and robust solutions compared to PBCE [1], [2], and [4].

To explore alternative design solutions and converge into an optimal, manufacturability knowledge should be integrated systematically into SBCE process. However, there is still no formal methodology aimed at integrating SBCE paradigm and manufacturability. Among others, questions that need to be answered include: How can designers be made aware of manufacturing capabilities and constraints in SBCE paradigm? How manufacturing planning can be executed in parallel with SBCE process?

This paper first tries to set the requirements of SBCE to start manufacturing planning (Section 2). Then, in Section 3, process planning literature has been explored to gain insight on how process planning can be executed in early phase of design. In Section 4, a methodological proposal is presented to answer the questions posed before. The proposed methodology is aimed at creating a dialogue mechanism through which product designers and manufacturing planners exchange knowledge about alternative designs and process plans. Besides, the methodology will be a support to choose an optimal solution from design and manufacturing perspectives. Finally, conclusion and future plans are briefed in section 5.

2 SBCE Requirements to start Manufacturing Process Planning

After investigating extensively the Toyota's product development process, Sobek et.al. [2], summarized the principles of SBCE as shown in Figure 2.

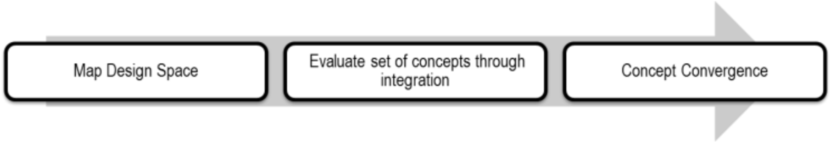


Fig. 2. Principles of Toyota's SBCE, modified from [2]

- **Map Design space**

"Map the design space" is how Toyota develops and characterizes sets of alternatives used in the SBCE process. In PD, Toyota applies this principle at component, subsystem and full product levels. Basically, the principle states that different functions involved in a PD should explore set of possible design alternatives from their own perspectives. Further, functions should communicate their feasible designs to other functions. The example in Figure 3 illustrates the key characteristics of SBCE. In Part A, the design and manufacturing functions define broad sets of feasible solutions from their respective areas of expertise.

- **Evaluate concept sets progressively through integration**

Once the feasible regions from different functions are defined, this principle states that functions should eliminate solutions which are proved to be infeasible from other functions' perspectives. However, unless there are sufficient data or knowledge to eliminate an alternative design it should be kept as an alternative. This principle makes SBCE different from PBCE. In the latter case, designers quickly select only one solution they think it is feasible without having sufficient data and knowledge to do so. Once that design proved to be infeasible late in a process, rework and process disruption emerges (as usually happens in practice [6]). In contrast, SBCE advocates delaying such decisions till enough knowledge is gathered through testing, simulations, and integrations. In Part B of Figure 3, for example, design engineers smoothly refines the set over time by eliminating ideas not feasible from manufacturing perspective and vice versa. And, only feasible solutions will be taken for further development.

- **Concept convergence**

As a design process matures and weak design solutions are eliminated through time, other functions should have also continually eliminate their infeasible plans in parallel. At a more detail phase, keeping wide design space is not recommendable both for efficiency and communication reasons. Keeping alternative designs can causes extra costs for the company to develop those concepts which might be not feasible in the future. Moreover, it helps other functions to base their planning activities on a robust design concept. Therefore, there should be a point at which optimal designs should be selected. As shown in Part C and D of Figure 3, although some uncertainty remains at latter phase of SBCE, design and manufacturing functions can agree on a rough design concept and a process plan.

The three principles of SBCE taken from Toyota PD sound logical and efficient. Moreover, among the many reasons for the outstanding performance records of Toyota PD, SBCE is mentioned as one of the key strategy [1], [2], [3], and [4]. To execute SBCE in practice though a formal procedure of exchanging information and knowledge between functions is required. Since manufacturability information is critical to execute SBCE, this paper focuses on formalizing the integration between SBCE design process with manufacturing process planning. A methodological approach is also suggested to dialogue both functions to effectively explore and converge into an optimal design and a process plan.

Based on the above principles, we identified the following key requirements that are needed to integrate design and manufacturing under SBCE paradigm:

- Integration between design and manufacturing should start at concept phase of design,
- Explore multiple set of solutions from design and manufacturing perspectives,
- Early communication about sets, based on preliminary design information,
- Impose minimum constraints to manufacturing and deliberately delaying specifications,
- Narrow sets gradually while increasing details until an optimal design and manufacturing plan are found.

  These requirements have significant implications for manufacturing process planning activities. Traditionally, process planning starts late in PD process or at detail design stages once a CAD model is finished. As a consequence, manufacturability problems then emerge causing delays and additional costs. Moreover, because design decisions are already been made, process planners traditionally cannot explore potential process alternatives as early as possible [2], [7]. Therefore, the integration of SBCE design strategy demands a new look on how process planning activities are done. Furthermore, a new methodology is needed that enables designers and process planers to explore and converge into optimal solution at early phase of design.

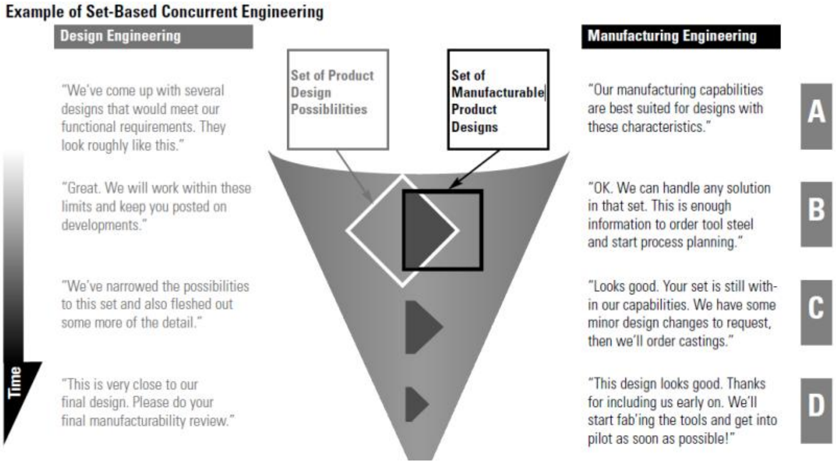


Fig. 3. Example of integration between design and manufacturing in SBCE paradigm [2]

3 Manufacturing Process Planning at Conceptual Design Phases

A manufacturing process planning is a method of selecting primary and secondary processes such as shaping, joining, or finishing a material. Also include selection of supporting processes such a fixture scheme, cutting conditions, etc. It is important to choose the right process-route at an early stage in the design before the cost-penalty of making changes becomes large [7]. A single component might go through several of those manufacturing processes (process-chains) to be finished. However, choosing the right process chains is not an easy task at conceptual phase of design. Because, only preliminary design information are available about the material, configuration, shape, etc. Therefore, at conceptual design stage there are many unpredictable factors in manufacturability, quality, reliability, serviceability [8]. As a result, process evaluation for a design is usually taken place at latest stages of a design and development process using computer aided process planning (CAPP) [9].

In order to start manufacturing planning at conceptual stage, rough methodological approaches have been suggested. Ashby's constrained based approach is the most prevalent one. Alternative process-chains are screened out based on process related parameters such as material types, shape, size, tolerance, etc. [10], [11]. Compatible process alternatives are then evaluated based on a rough cost estimation such as resource based costing [10], [11]. Detail costing methods, such as ABC costing [12], are not applicable at conceptual stages since such methods require detail data about the design [10], [11]. In terms of process planning for quality, the classical capability index, which is defined as the ratio of dispersion to tolerance (i.e. $C_p=T/6\sigma$), is not suitable during conceptual stages. The C_p is only suitable for medium and large batch production modes when standard deviations (σ) can be determined [13]. Composite process capability (CCP) index has been suggested to be used during early phase of design and when data are not sufficiently available [13]. The details of CCP will be introduced in Section 4.

In SBCE paradigm, there are alternative set of conceptual designs. For each alternative design, there are alternative process chains that should be investigated to be feasible from manufacturability perspective. Here the challenges and questions are: a) how designers and process planner can exchange knowledge about the potential solutions? b) how alternative designs and processes can be evaluated in parallel in SBCE paradigm to reach optimality?

Taking cost and quality as key criteria for process planning, the following section outlines the steps of the proposed methodology.

4 Proposed Methodology to start Manufacturing Process Planning in SBCE Paradigm

The proposed methodology is shown in Figure 4. The methodology includes four steps: a) identification of key quality characteristics for alternative set of designs, b) planning for process quality using an integrated Quality Function Deployment (QFD) approach and a Process Failure Mode and Effect Analysis (P-FMEA), c) assessment of process quality and cost for each set of designs using CCP index and resource based costing, d) build a decision matrix relating conceptual design alternatives with respect to process-chain alternatives.

The methodology is designed assuming that designers are following a SBCE paradigm, and have already explored alternative set of conceptual designs. Moreover, at the start of the methodology, process planners already have important elements of manufacturing process alternatives to produce the conceptual designs. Let’s take a scenario to exemplify the steps of the methodology.

XYZ is a company developing and manufacturing ball bearings in a large scale, but also offering customized solutions for the automotive industry. XYZ is asked to supply a new ball bearing for a new automobile model. The designers of XYZ come up with three alternative bearing concepts: A1, A2 and A3 (see Figure 4). The design team argue that to investigate the feasibilities of the alternative bearings and select the optimal one, they need the manufacturability information of the alternatives. At the same time, the management wants to start designing the manufacturing process in parallel with the product development to avoid late changes. Manufacturing process planners roughly identified key process elements required to produce the bearing, such as, Machining method (MM), Machining tool (MT), and Fixture scheme (FS). For each process elements they identified process alternatives: Finish or Semi-finished turning for machining (MM1 or MM2), Vertical or Horizontal lathes for *machining tool (MT1 or MT2), and Final or Outer-clamping (FS1 or FS2) for fixture scheme respectively. Therefore, in this case we have 3 alternative design concepts and 8 (2X2X2)alternative process-routes (process-chains) to evaluate.*

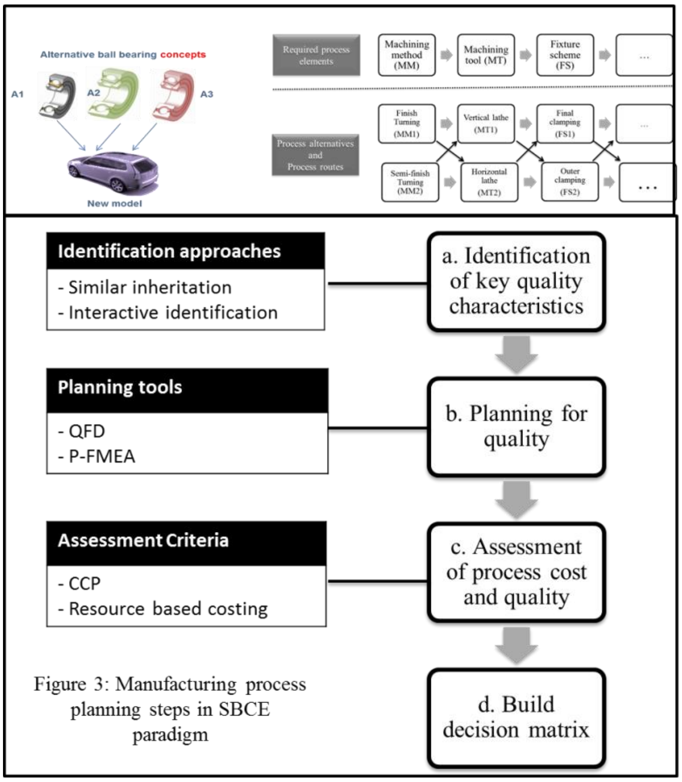


Fig. 4. Steps of the proposed methodology

— Identification of key quality characteristics

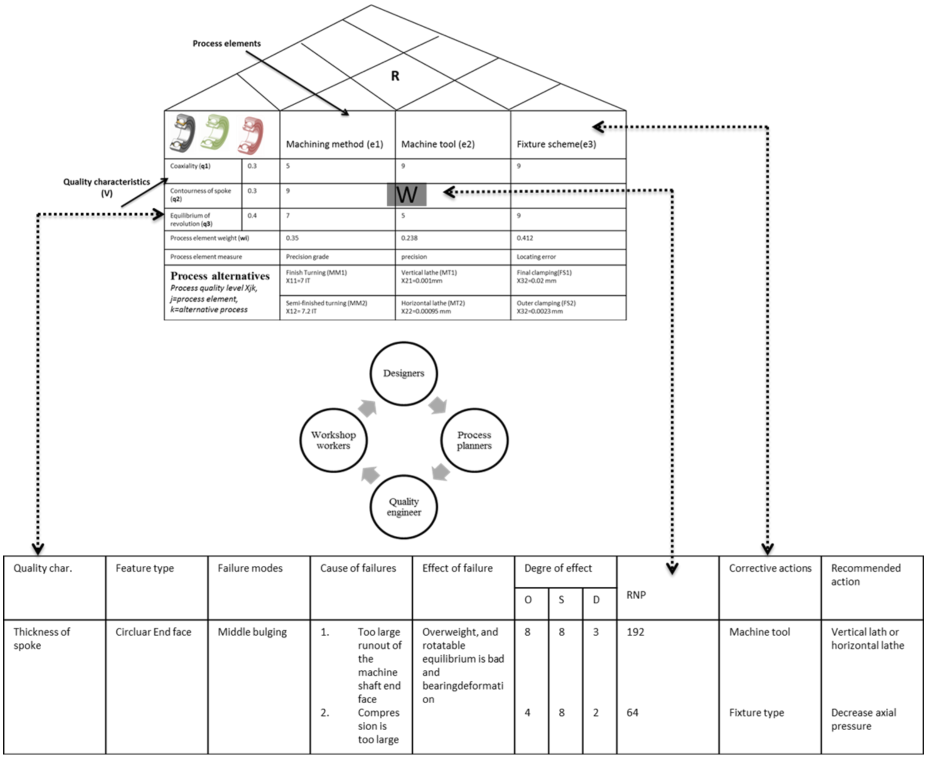
Once the sets of alternative of designs and process routes are identified, defining key design quality characteristics is necessary. Quality characteristics are requirements specified to fulfill defined customer values. For a specific component or module, key quality characteristics can be identified either taking similar component family (similar inheritation) or through expert negotiation (interactive identification). For instance, co-axiality, contourness of spoke and equilibrium of revolutions are the common quality characteristics of the ball bearings introduced in the XYZ scenario.

— Planning for quality

The task of this step is to relate the defined quality characteristics of the conceptual design sets into process elements and their target levels. To roughly determine the capability of process alternatives, a team consists of designers, process planners, and quality engineers should be organized.

Product designers determine the weights of each quality characteristics based on their experiences about customer needs and design specifications. Using QFD as a tool to represent the voice of customers, designers can assign the importance of each quality characteristics. For the scenario mentioned above, assume that the designers assigned weights of V[0.3, 0.3, 0.4] for the three quality characteristics defined: co-axiality, contourness of spoke and equilibrium of revolutions respectively.

Process planners and quality engineers can use P-FMEA to estimate the quality impact of each process elements on the quality characteristics. Based on past experience and knowledge from historical comment, they can estimate O (Occurrence), S (Severity), and Detectability (D) of process failures relating a specific quality characteristics and a process element. Then, an aggregate RNP (risk priority number=O*S*D) value can be obtained from P-FMEA. Depending on the RNP value, the relationship between process elements and quality characteristics can be scaled on a QFD matrix from 1-10 (1 very weak relationship and 10 highly related), see Figure 5. The relative weight of each process elements (W) can be determined using the normal QFD algorithm [14]. This weight matrix relates the importance of each process elements (Machining method, fixture scheme etc.) with the defined key quality characteristics.



		Machining method (e1)	Machine tool (e2)	Fixture scheme(e3)
Coaxiality (**q1**)	0.3	5	9	9
Contourness of spoke (**q2**)	0.3	9	W	
Equilibrium of revolution (**q3**)	0.4	7	5	9
Process element weight (**wi**)		0.35	0.238	0.412
Process element measure		Precision grade	precision	Locating error
Process alternatives *Process quality level Xjk, j=process element, k=alternative process*		Finish Turning (MM1) X11=7 IT	Vertical lathe (MT1) X21=0.001mm	Final clamping(FS1) X32=0.02 mm
		Semi-finished turning (MM2) X12= 7.2 IT	Horizontal lathe (MT2) X22=0.00095 mm	Outer clamping (FS2) X32=0.0023 mm

Quality char.	Feature type	Failure modes	Cause of failures	Effect of failure	Degre of effect			RNP	Corrective actions	Recommended action
					O	S	D			
Thickness of spoke	Circluar End face	Middle bulging	1. Too large runout of the machine shaft end face	Overweight, and rotatable equilibrium is bad and bearingdeformation	8	8	3	192	Machine tool	Vertical lath or horizontal lathe
			2. Compression is too large		4	8	2	64	Fixture type	Decrease axial pressure

Fig. 5. An illustration of process planning for quality with a hybrid approach (QFD and Process-FMEA)

For each process element the quality measure and level should be defined on the QFD matrix. For example, the process element measure of machining method is precision grade. And, for each alternative machining methods the element level can be defined accordingly. For example, finish and semi-finish turning have precision grade of 7 and 7.21 IT respectively. Therefore, using the integrated QFD and P-FMEA the team can prepare all the parameters to determine the composite process capability index (CCP) for each process alternatives.

- **Assessment of process quality and cost**

Cost estimation at conceptual stage is already a matured concept in academia and industry. Using resource based costing one can determine the process cost of each design alternatives [10], [11]. Therefore, in this paper, process cost values are assumed to be given. However, the step to determine the quality level of process alternatives are not well prevalent, and can be explained as follows:

Step 1. Estimate the capability of process alternatives (Ce_j)

$$Ce_j = \left[1 + \left(\frac{X_j - X_j^0}{X_j^{Max} - X_j^{Min}}\right)\right] \tag{1}$$

where Ce_j is the capability index of the j^{th} process alternative of a process element. X_j, X_j^0, X_j^{Max} *and* X_j^{Min} are the quality measure, the standard or benchmark, the upper and lower limits of the jth process alternative respectively. The standard process alternative is generally either an enterprise standard or a straightforward process alternative with which the team members are very familiar. It can also be a successfully available process alternative, or an earlier generation of the manufacturing process.

Step 2. Estimate the capability of the quality characteristics (Cp_i)

$$Cpi = \sum_{j}^{n} w_{ij} . Ce_j \tag{2}$$

Where Cp_i is the capability of the i^{th} quality characteristics, w_{ij} is the weight of process elements that relate the i^{th} quality characteristic with the j^{th} process element. And, n is the number of process elements available.

Step 3. Estimate the composite process capability indexes (CCP) of alternative process routes

$$CCP = \prod_{i=1}^{m} (Cp_i)^{V_i} \tag{3}$$

Where m is the number of quality characteristics available and Vi is the weight of the ith quality characteristics.

If we consider the XYZ company scenario again, using step1 it is possible to determine the C_{ej} indexes of alternative process plans, as shown in Table 1.

Using the relative weight found using QFD and P-FMEA, a weight matrix W_{ij} can be defined as shown in Table 2. Next, using step 2 the team can determine the C_{pi} indexes of the quality characteristics as shown in Table 3. The output of this step shows the capability of each process alternatives (routes or chains) for the defined key quality characteristics. Since we have 8 possible process chains (2X2X2), each quality characteristics has 8 possible values of C_p, as shown in Table 3. For example, a design can go through MM1-MT1-FS1 or MM1-MT1-FS2 possible process chains. Moreover, using step 3 the aggregate process capability index of alternative process chains can be determined, assuming the importance of each quality characteristics as V_i [0.3, 0.3, 0.4], see Table 4.

Table 1. Ce_j indexes of alternative processes

	Machining methods (MM)	Machine tool (MT)	Fixture scheme (FS)
C_e Values	MM1=1.49	MT1=1.11	FS1=1.54
	MM2=1.3432	MT2=1.2	FS2=1.55

Table 2. W_{ij} indexes of process elements

W_{ij}	Machining methods (MM)	Machine tool (MT)	Fixture scheme (FS)
Coaxiality	0.3	0.2	0.5
Contourness of spoke	0.3333	0.3333	0.333
Equilibrium of revolution	0.3	0.3	0.4

Table 3. C_p-capabilities of quality characteristics

Cp	MM1-MT1-FS1	MM1-MT1-FS2	MM1-MT2-FS1	MM1-MT2-FS2	MM2-MT1-FS1	MM2-MT1-FS2	MM2-MT2-FS1	MM2-MT2-FS2
Coaxiality	1.43	1.44	1.45	1.35	1.26	1.26	1.31	1.31
Contourness of spoke	1.37	1.38	1.40	1.36	1.33	1.33	1.36	1.36
Equilibrium of evolution	1.39	1.35	1.42	1.42	1.35	1.35	1.37	1.38

- **Build decision matrix**

A decision matrix that relates alternative designs and process chains help designers and process planners to dialogue while practicing a SBCE process. Since each conceptual product design has particular quality performance and cost structure, the team should follow the above procedures a, b and c to determine the CCP and cost values of alternative process chains for each design. Finally, at this stage a decision matrix can be built to visually represent design and planning spaces, and the team can utilize to decide an optimal design in parallel with an optimal process plan, as shown in Table 5.

Table 4. CCP values of alternative process chains

CCP	MM1-MT1-FS1	MM1-MT1-FS2	MM1-MT2-FS1	MM1-MT2-FS2	MM2-MT1-FS1	MM2-MT1-FS2	MM2-MT2-FS1	MM2-MT2-FS2
	1.40	1.39	1.43	1.37	1.32	1.32	1.35	1.36

Table 5. Final decision matrix or dialoguing mechanism between designers and process planners

Alternative Process Chains		*MM1-MT1-FS1*	*MM1-MT1-FS2*	*MM1-MT2-FS1*	*MM1-MT2-FS2*	*MM2-MT1-FS1*	*MM2-MT1-FS2*	*MM2-MT2-FS1*	*MM2-MT2-FS2*
 A1	CCP1	1.40372	1.38977	1.42899	1.386534	1.31884	1.319461	1.35234	1.3555177
	Cost1	-	-	-	-	-	-	-	-
 A2	CCP2	1.40000	1.48997	1.32999	1.23653	1.3432	1.2345	1.37234	1.9555177
	Cost2	-	-	-	-	-	-	-	-
 A3	CCP3	1.30372	1.58977	1.72899	1.386534	1.11884	1.419461	1.65234	1.3555177
	Cost3	-	-	-	-	-	-	-	-

5 Conclusion and Future Plan

This paper aims at developing a formal methodology to integrate designers and process planners to execute SBCE. Extensive literature review has been made to outline key manufacturing requirements of SBCE, to understand the key intercept points of design and manufacturing in SBCE paradigm. The new methodology is based on the combination of the two prevalent tools, QFD and P-FMEA. The methodology enables both parties to exchange knowledge about designs and processes in parallel. Moreover, using CCP and cost indexes, design and process-chain alternatives can be evaluated systematically.

The methodology is under validation in a real case. The next step is to apply it in a specific SBCE environment.

Acknowledgements

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